Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA

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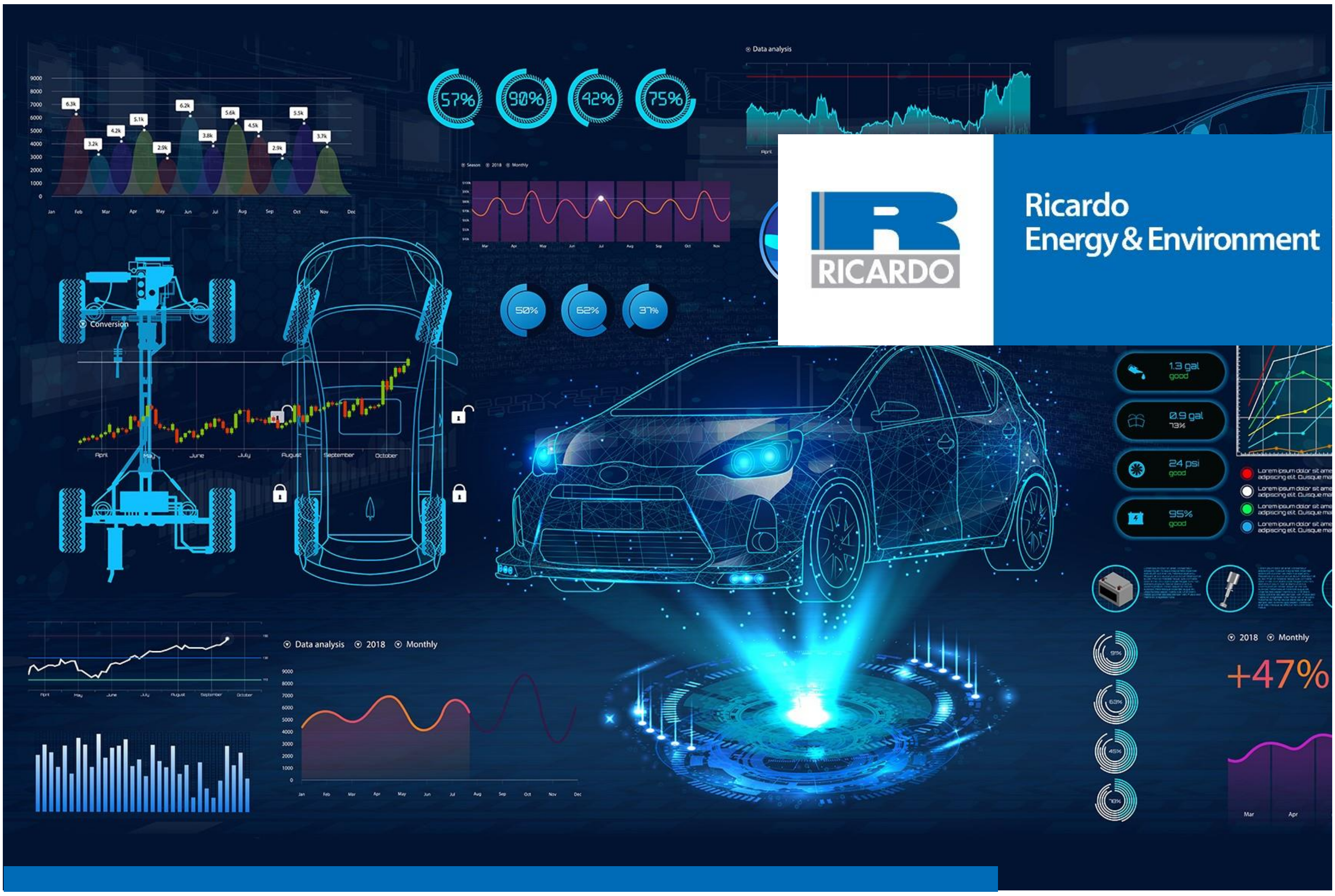

Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA

Final Report for the European Commission, DG Climate Action

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Abstract

EN:

Transport is an important contributor to several environmental issues, including air pollution and climate change. The EU has set challenging objectives for tackling these. To help support decision making on mitigating actions in the transport sector it is paramount to develop a better understanding of the environmental impacts of road vehicles over their *entire* lifecycle. This report summarises a range of vehicle life-cycle assessment (LCA) studies available in the public domain, which were found to be of varying focus, data quality, detail and coverage. It develops a policymaker-oriented LCA methodology for light- and heavy-duty vehicles covering a selection of major powertrain types and fuel chains for the 2020 to 2050 timeframe. The study has combined state-of-the art vehicle LCA with novel methodological choices to develop results for a range of environmental impacts for 14 electricity chains, 60 fuel chains, and 65 generic vehicle/powertrain combinations across 7 vehicle types. It has also provided several suggestions for policy-makers, based on these results, especially recommendations for future LCA research.

DE:

Der Verkehr trägt entscheidend zu verschiedenen Umweltproblemen bei, darunter Luftverschmutzung und Klimawandel. Die EU hat sich anspruchsvolle Ziele für deren Bewältigung gesetzt, und um die Entscheidung über geeignete Minderungsmaßnahmen im Verkehr zu unterstützen, ist es von größter Bedeutung, ein besseres Verständnis der Auswirkungen von Straßenfahrzeugen während ihres gesamten Lebenszyklus zu entwickeln. Dieser Bericht fasst eine Reihe von öffentlich zugänglichen Fahrzeug-Lebenszyklusanalysen (LCA) zusammen, die sich in Ausrichtung, Qualität, Detailgrad und Abdeckung unterscheiden. Er entwickelt eine an politische Entscheidungsträger gerichtete Ökobilanzmethodik für leichte und schwere Nutzfahrzeuge, die eine Auswahl wichtiger Antriebsstränge und Kraftstoffketten für den Zeitraum 2020 bis 2050 abdeckt. Die Studie kombiniert dabei eine Fahrzeug-LCA nach aktuellem Stand der Wissenschaft mit neuartigen methodischen Ansätzen, um die verschiedenen Umweltauswirkungen für 14 Stromerzeugungsarten, 60 Kraftstoffvorketten und 65 generische Fahrzeug-/Antriebsstrangkombinationen für 7 Fahrzeugtypen zu bilanzieren. Darüber hinaus gibt sie auf der Grundlage dieser Ergebnisse zahlreiche Empfehlungen für politische Entscheidungsträger, insbesondere Empfehlungen für zukünftige LCA-Forschung.

FR:

Les transports génèrent de multiples impacts environnementaux et contribuent particulièrement à la pollution atmosphérique et au changement climatique. L'UE a défini des objectives ambitieux afin de les réduire. Pour les atteindre, il est essentiel de développer une meilleure compréhension des impacts environnementaux des véhicules sur l'ensemble de leur cycle de vie. Cette étude s'appuie sur une revue approfondie des l'Analyses du Cycle de Vie (ACV ou LCA en anglais) disponibles dans le domaine public et dont le périmètre d'étude, la méthodologie appliquée, le niveau de détail et la qualité des données varient considérablement. Le présent rapport s'adresse principalement aux décideurs politiques et décrit la méthodologie d'Analyse du Cycle de Vie développée par notre consortium sur un grand nombre de véhicules légers et poids lourds, tout en couvrant les principaux types de propulsion (thermique/électrique) et de carburants sur une période allant de 2020 à 2050. L'étude s'appuie sur une combinaison méthodologique d'approches d'ACV bien établies et d'éléments plus novateurs permettant d'évaluer l'impact environnemental de 14 chaines de production électrique, 60 chaines de production de carburants et 65 combinaisons véhicule/train roulant pour 7 types de véhicule. Elle fournit également un certain nombre de suggestions adressées aux décideurs politiques sur la base des résultats, et tout particulièrement des recommandations concernant la recherche future dans le domaine des ACV.

Executive Summary

Introduction and context

In the transport sector, a number of EU-level policies have been put in place to tackle sectoral environmental impacts and support the transition towards a low-carbon, circular economy. Road transport, in particular, is responsible for a range of environmental impacts. To inform decision-making, it is paramount to develop a better understanding of the environmental impacts of road vehicles over their *entire* lifecycle. The vehicle use phase accounts for the most significant proportion of the lifecycle impacts of gasoline/diesel vehicles, but lower emission fuels, improved emissions control, and alternative drivetrains increase the relevance of assessing environmental impacts in the other life stages.

When based on consistent methodological choices and comparable levels of data robustness, life-cycle assessment (LCA) enables comparison of different vehicle technologies and fuel options, on a like-for-like basis. It can help identify key impacts and hotspots throughout the different life cycle stages, in order to better understand the range of opportunities to reduce them, as well as mitigate any potential burden shifting. The European Commission's DG Climate Action therefore commissioned Ricardo Energy & Environment (together with ifeu and E4tech) to provide technical support to the European Commission in this area by carrying out a *"Pilot study on determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment"* (hereafter, 'this study').

The aim of this study is to improve the understanding of the environmental impacts of road vehicles and the methodologies to assess them in the mid- to long-term timeframe (up to 2050). It covers a selection of light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) with different types of powertrains (internal combustion engine and/or electric engine powered by fuel cells or batteries) and using different types of energy (of fossil and/or renewable origin). It has two main objectives:

1. To develop an approach for a LCA of road vehicles, including the fuels or electricity which power them, based on a literature review and stakeholder consultation, and combining mainstream elements of vehicle LCAs with novel methodological choices where necessary.
2. To apply this approach to understand the impacts of methodological choices and data sources on the LCA results for selected vehicle/powertrain/fuel categories expected to be in use over the time period 2020 to 2050.

The LCA approach used in this study covers a broad range of environmental impacts caused by the manufacturing, use and end-of-life phases of selected vehicle categories.

The methodological choices made in this study, including the specific modelling of environmental impacts and the choice of datasets, are transparent and build on available literature and datasets. The choices made are based on fulfilling the specific objectives of the study, and have been (as far as feasible) consistently applied across all of the different vehicle, fuel/electricity chain and powertrain types. However, the breadth of the study did not allow for a consistent level of robustness and validation of all data, which, in several instances, were limited, especially for certain more novel energy and fuel chains. There were also some fuel chains where alternative or more novel methodological options were explored in order to understand their impacts. The impacts of these alternative methodological options are explored in the study through sensitivity analyses, and results for fuel chains were not included in the overall vehicle LCA analysis where data or methodological choices were judged insufficiently robust.

Overall vehicle LCA outputs from this study provide robust and internally consistent indications on the relative life-cycle performance of the different options considered, particularly for vehicle powertrain comparisons, electricity chains, and conventional fuels. The study also provides good evidence on how temporal and spatial considerations influence lifecycle performance and how potential future developments (in technology or electricity supply) are likely to affect these powertrain comparisons.

Review of evidence and stakeholder consultation

The development and application of the LCA methodology was informed by evidence and data collected through both literature review and stakeholder consultation activities as shown in Table ES1 and Table ES2. Throughout the course of the study, over 350 literature sources were evaluated with contributions provided by over 100 stakeholder organisations from academia, industry, policymakers and NGOs.

Table ES1: Overview of main research tools used in this study

Tool	Objectives	Activities
Literature review	An extensive review of the literature on LCA of vehicles, key components and transport energy carriers was undertaken to support the development of proposals for the LCA methodology and collect key data to feed into the application of the methodology.	Desk research Rapid Evidence Assessment (REA) Data requests
Stakeholder consultation	A range of stakeholder consultation activities were organised throughout the course of the study to support the development and application of the methodology, and to aid data collection, fill data gaps and validate key assumptions.	Delphi Survey Workshops and meetings Data validation exercises Data requests

Table ES2: Stakeholder consultation carried out in this study

Activity	Description	Contribution:
Delphi survey	Two-round survey to confirm methodological aspects that are particularly complex or involve significant uncertainty.	Development of the LCA methodology
Workshops and meetings	An LCA expert workshop to present initial methodology proposals, the literature review findings, and first-round survey results, and gather feedback from stakeholders to validate key methodological issues. A final meeting to present and discuss draft findings from the work and recommendations.	Development of the LCA methodology Application of the LCA methodology General conclusions
Data validation exercises and ad-hoc data requests	Two validation exercises, and ad-hoc data requests were used to gather/validate data and key assumptions to be used in the application of the methodology.	Application of the LCA methodology.

The literature review found that there is a strong focus in the literature on:

- Certain environmental impact categories: greenhouse gas emissions or GWP (i.e. global warming potential) is the most common category.
- Certain vehicle types: passenger cars dominate, with few examples of lorry and bus LCAs.
- Conventional fuel/energy types, e.g. petrol, diesel, electricity.

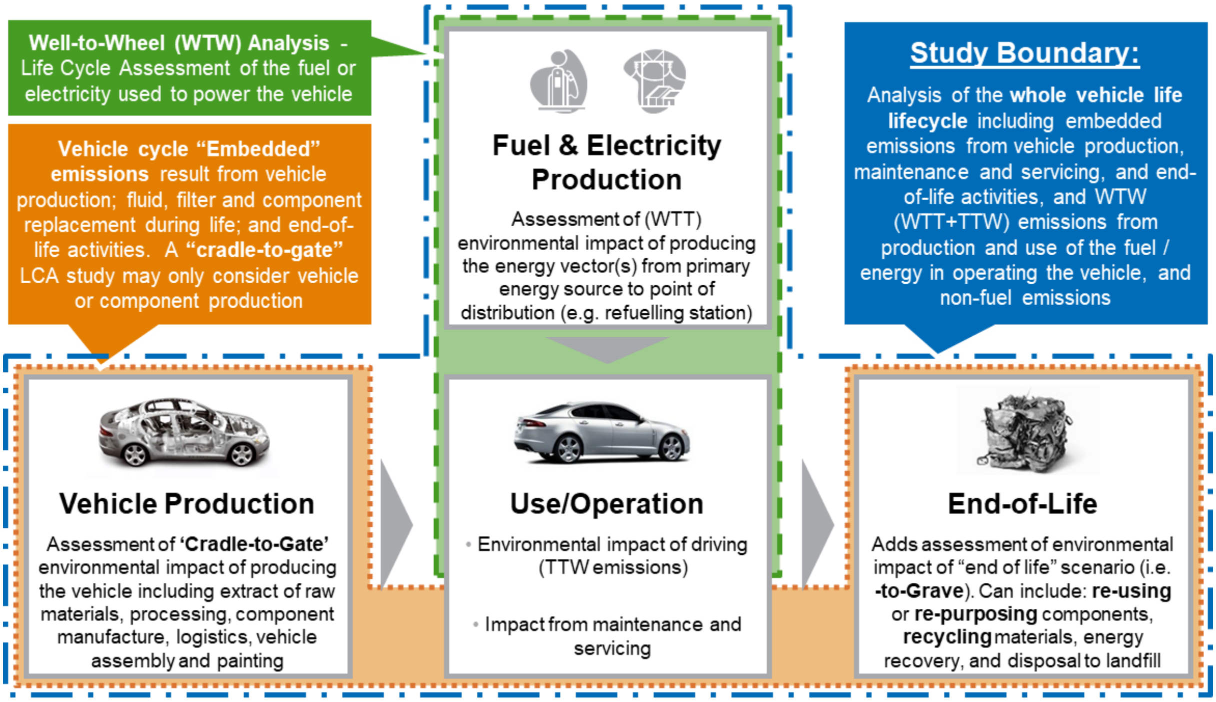
Detailed assessment of the key studies identified showed that there is significant variability in the results reported, due to differences in data sources and modelling. Nevertheless, the assessment generally confirmed conclusions from previous literature reviews on the relative contribution of different life cycle stages, and environmental hotspots for different vehicles, powertrain and energy carriers, namely that operational impacts dominate for conventionally fuelled vehicles, and manufacturing impacts are much more important for electric vehicles. The detailed findings from the review were used to help prioritise the work on the development and application of the LCA methodology, and to inform the subsequent consultation on these aspects with stakeholder experts.

Development and application of the LCA methodology

The first step in an LCA is to define the goal and scope of the LCA. The goal of this LCA is to explore the environmental impact of a representative selection of road vehicle configurations in a holistic manner. The LCA approach covers vehicle production, use/operation of vehicles including fuel and electricity production, as well as vehicle end-of-life. This is illustrated in Figure ES1 which shows the LCA system boundary.

This study aims to enhance the Commission's understanding of environmental impacts and of suitable methodologies to assess them in the mid- to long-term time frame (until 2050). The intended audience is therefore foremost the European Commission and decision-makers more at large.

Figure ES1: Schematic scope of the assessment (system boundaries)



Note: Infrastructure for energy production (electricity and fuels) is also included. Electricity storage is excluded.

The analysed product systems are selected configurations of light- and heavy-duty vehicles, including two cars, a light commercial vehicle/van, a small rigid lorry, a large articulated lorry, an urban bus and a coach[1]. These were evaluated for a range of powertrain combinations which are meaningful for the vehicle body type, as indicated in Table ES3 – which include both conventional powertrains and a range of different xEV powertrains[2]. The characteristics of the body type are adjusted as necessary when different powertrains are used (as outlined in the main report Sections 3.5 and 3.6), to allow for the impact of the powertrain on the presence and sizing of individual components.

The assessment of impacts includes 14 different impact categories[3], ranging from impacts associated with airborne emissions (e.g. the mid-point indicator GWP for greenhouse gas emissions) to impacts from resource use (e.g. energy consumption and water scarcity). Additionally, results are also provided for a subset of specific greenhouse gas and air pollutant emissions based upon their regulatory significance for transport, including CO_2, CH_4, N_2O, CO, NH_3, NMVOC, NO_x, PM_{10}, $PM_{2.5}$ and SO_x.

Table ES3: Summary of vehicle types and segments covered in the analysis

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV*	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck	Typical SD, 24 t GVW
Gasoline ICEV	Y	Y				
Diesel ICEV	Y	Y	Y	Y	Y	Y
CNG ICEV	Y	Y	Y***		Y***	Y***
LPG ICEV	Y	Y				
LNG ICEV			Y***	Y***	Y	Y***

[1] Further information on European vehicle classifications are available here: https://www.eafo.eu/knowledge-center/european-vehicle-categories
[2] xEVs are defined in this study to include PHEV (plug-in hybrid electric vehicle), REEV (range-extended electric vehicle), BEV (battery electric vehicle) and FCEV (fuel cell electric vehicle).
[3] All impact categories from the PEF (Product Environmental Footprint) guide (JRC, 2018a) were considered, but to reduce uncertainty, the assessment relies on commonly established midpoint indicators instead of more aggregated endpoints.

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV*	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck	Typical SD, 24 t GVW
Gasoline HEV	Y	Y				
Diesel HEV	Y	Y	Y	Y	Y	Y
Gasoline PHEV	Y	Y				
Diesel PHEV	Y	Y	Y	Y	Y	Y
BEV	Y	Y	Y	Y	Y	Y
FCEV	Y	Y	Y	Y	Y	Y
FC-REEV			Y	Y		Y
Diesel HEV-ERS				Y		
BEV-ERS				Y	Y**	

Notes:

* Key vehicle characteristics defined based on EU registrations-weighted averages for: Lower Medium = defined as segment C vehicles (e.g. VW Golf) and medium SUVs (e.g. Nissan Qashqai); Large SUV = Large SUVs / Crossovers (e.g. BMW X5, Land Rover Range Rover, Volkswagen Touareg, Volvo XC90, etc.).

**Urban bus using regular ultra-rapid charging via a pantograph connection at stops along its route, enabling a significantly smaller on-board battery. Not a trolleybus.

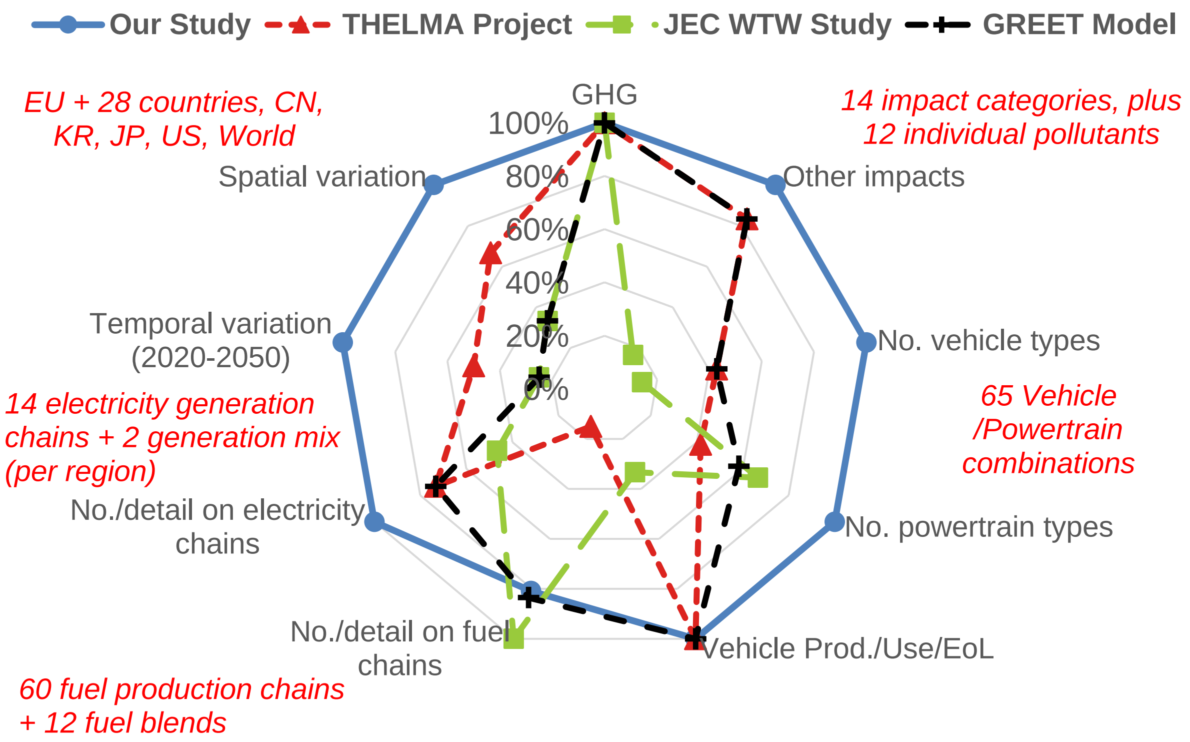
*** Modelled with two alternative engine variants each: -CNG and -CNG lean-burn; -LNG and -LNG/Diesel HPDI.

Figure ES2 illustrates the broad and comprehensive scope of this vehicle LCA compared with the most detailed reference studies and vehicle LCA models found in the literature review. The LCA methodological choices made for this study were based on the literature review and stakeholder consultation process and are generally in accordance with the norms set out for performing a LCA in (ISO14040, 2006) and (ISO14044, 2006). They were guided by the goal and scope defined for the LCA, but were tempered by the practical feasibility of applying them. Other aspects taken into account in making methodological choices were the relevance of the overall impact, the appropriateness for the object of investigation and the suitability for a spatial and temporal differentiation.

Figure ES3 provides a high-level overview of the framework for applying the project's LCA methodology and shows the key data flows. A modular LCA calculation approach was developed as this allows for the calculation of results from the study in a systematic and flexible way. It also facilitates the use of a wide range of alternative data input settings to enable the exploration of key sensitivities and uncertainties in these.

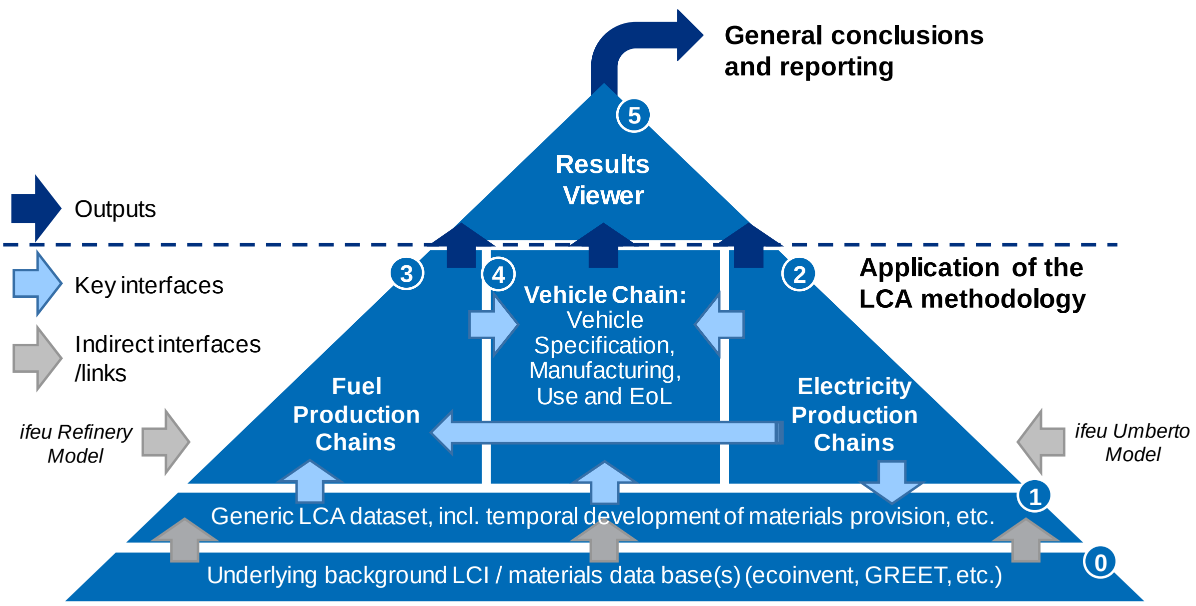
A separate stand-alone 'Results Viewer' module is available alongside this final report, providing a more detailed and comprehensive set of results.

Figure ES2: Illustration of the comprehensive scope of this vehicle LCA study compared with other detailed studies and models identified the literature review



Sources: The THELMA project: (PSI/EMPA/ETHZ, 2016), JEC Well-To-Wheels study: (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b); the Argonne National Laboratory's GREET lifecycle model: (ANL, 2018).

Figure ES3: Overview of the LCA application framework and key data flows



Notes: Data calculation/flows are carried out in the indicated order from 0 (background LCI) to 5 (results).

Results from the application of the methodology

The implementation of the developed methodology has provided results for the study covering:

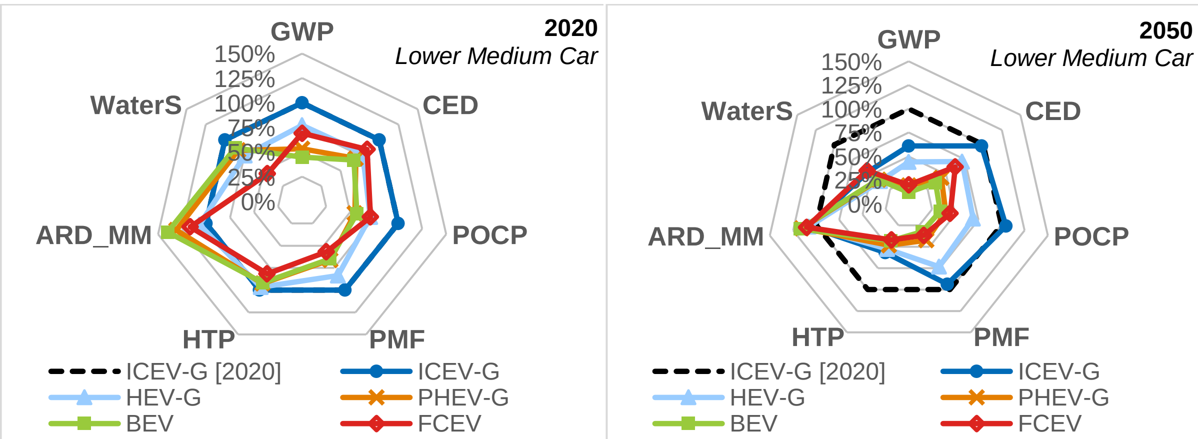
- Two **high-level scenarios** based on analysis supporting the Commission's Long-Term Strategy (Commission Communication COM(2018) 773), i.e. Baseline and a lower carbon future - Tech1.5 scenario, consistent with the EU contribution to meeting the Paris Agreement objective of keeping global temperature increase to a 1.5 ºC max).
- 14 different **electricity production chains**, covering the EU28 and its individual Member States (relevant for vehicle manufacturing, and electric vehicle operation), and five other world regions (China, S. Korea, Japan, the US and the global average) (for manufacturing only).
- 60 different **liquid and gaseous fuel production chains**, covering 5 fuel categories, 21 feedstocks, and over 20 processes, plus two fuel mix/blend scenarios for each fuel category.
- 65 different generic **vehicle type/powertrain combinations**, across six light- and heavy-duty vehicle body types.
- 14 different **sensitivities** exploring the significance and impacts of key assumptions and uncertainties for the comparative analysis of different vehicles/powertrain and fuel types.

The results presented in the main report and the accompanying 'Results Viewer' provide a harmonised and consistent comparison of the environmental performance of a sample of vehicles for all stages of the vehicle life-cycle. This broad and deep dataset allows for the further investigation of individual impacts, as well as for comparing across different impact categories. This is illustrated in Figure ES4 below for lower medium cars (market segment C).

In broad terms, the analysis shows that xEV powertrains have significantly lower environmental impacts across all vehicle types and most impact categories, with BEVs consistently performing better than all other powertrains. The higher impacts in some categories for xEVs (e.g. abiotic resource depletion, minerals and metals - ARD_MM) are generally due to the use of particular materials (particularly copper and electronic components). The analysis also demonstrates that xEV benefits in terms of lower environmental impacts vary depending on regional and operational circumstances. Figure ES5 shows how (relative) GHG impacts of xEV vary between countries, primarily due to differences in country electricity generation mixes (as a proxy to carbon-intensity of electricity supplied to transport end users), and, to a smaller extent, in urban/rural/motorway road driving shares and climatic conditions.

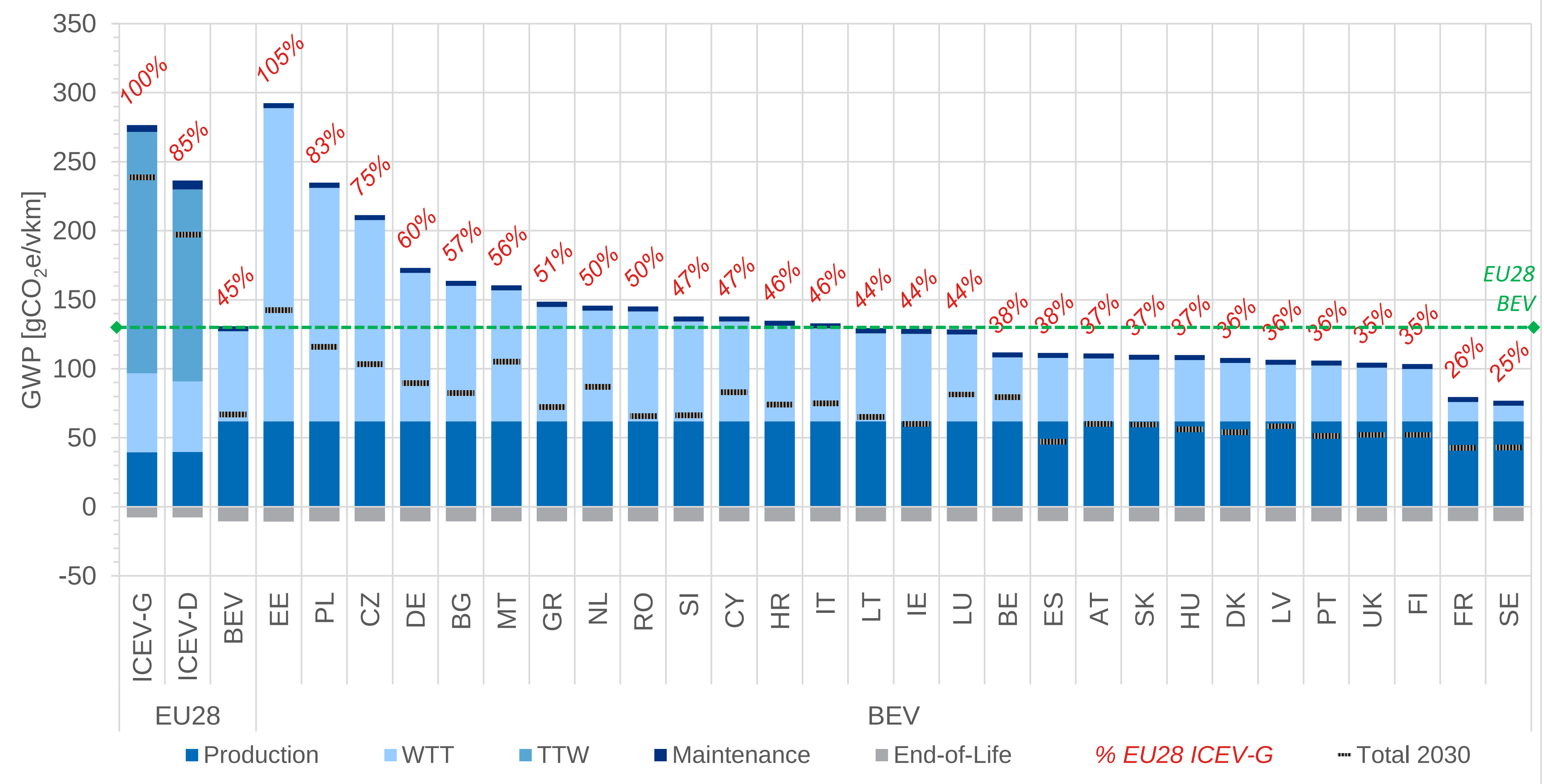
The results also show the lower impacts of gas-fuelled vehicles compared to diesel or gasoline fuelled vehicles. For example, Figure ES6 shows how lorries fuelled by liquefied natural gas (LNG) and buses running on compressed natural gas (CNG) show benefits across several environmental impact categories compared to diesel vehicles.

Figure ES4: Summary of the relative impacts for Lower Medium Cars for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050 (Tech1.5 Scenario)



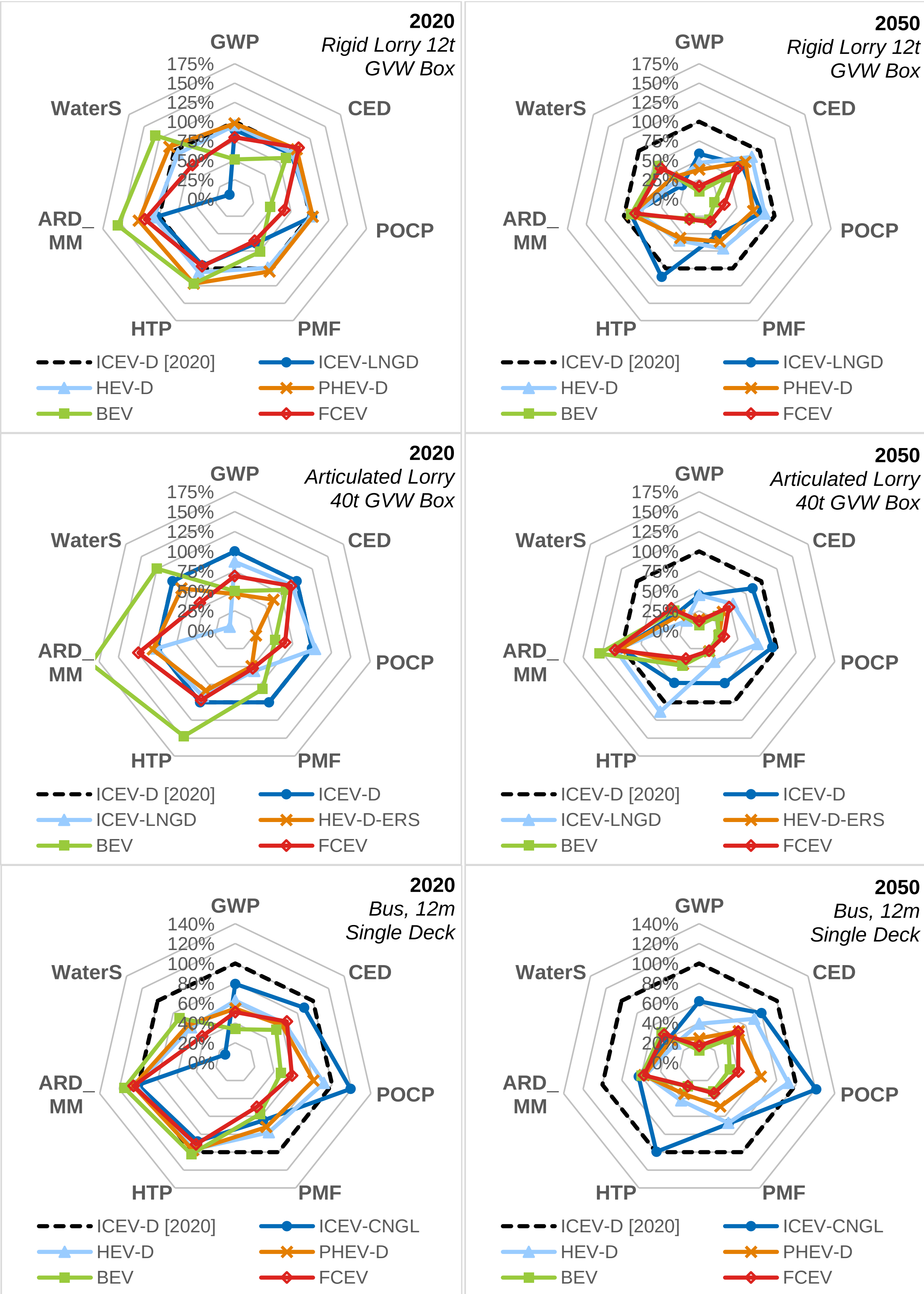
Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%.
Powertrain types: G- = Gasoline; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle.
LCA impacts: GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity.

Figure ES5: Comparison of Lower Medium Car lifecycle GWP impacts for conventional gasoline/diesel ICEVs and BEVs for different EU countries, Baseline scenario. Breakdown shown for new 2020 vehicles, and the total only for new 2030 vehicles.



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range (and with 64 kWh and 460 km WLTP electric range for 2030); an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEVs.

Figure ES6: Summary of the relative impacts for Rigid and Articulated Lorries, and Urban Buses for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Tech1.5 Scenario.



Notes: LNGD = LNG HPDI engine, using ~5% diesel; CNGL = CNG Lean-burn engine; HEV-D-ERS = Hybrid with pantograph enabling operation on overhead line electric road system (ERS). Other abbreviations as in Figure ES4.

Key limitations and uncertainties for the analysis

The results presented in this report are characterised by a good degree of "internal consistency", i.e. they generally allow for like-for-like comparison of different vehicles within the boundaries, the data sources, and the data processing (methodological) choices valid for the purpose of this study.

However, it is not generally valid to compare the results from this study with those of other studies characterised by their own analytical boundaries, different data sources, and specific data processing choices. As a result, this study cannot be considered to provide definitive, absolute results on the environmental impacts of different vehicles.

For fuels, different methodological approaches, assumptions and data sources are tested in this study, some of which were novel in nature or utilised data with significant underlying uncertainty. This means that the results should not be taken as an accurate, consistent representation of impacts across *all* of the fuel chains investigated. (An assessment of the robustness of different fuel chains is provided in the report Appendices). In addition, comparisons should not be made between fuel chains when these are evaluated via different methodological approaches or where data robustness is more limited. To mitigate for such cases, in the overall vehicle LCA analysis, such fuel chains were generally not included in the fuel blends used, and the more novel methodological options were reserved for the sensitivity analyses.

The study shows (with a wide range of sensitivities) the consequences of methodological choices and key assumptions used in the LCA on the resulting environmental impacts of vehicle and energy chains and how potential future developments may affect these comparisons.

Overall conclusions and recommendations

Despite the ambitious scope of the study, the methodology and background data could be harmonised to a great extent for all stages of the life-cycle leading to a good comparability of the results for vehicles. The comparability of individual fuel chains is more limited because of methodological complexity and robustness of data sources. Accordance with the general principles of ISO and other important guidelines (PEF, ILCD) could mostly be established. Stakeholder consultation carried out as part of the study predominantly favoured the chosen methodological approaches, helping to confirm that the key criteria for the methodology development had been met.

The results of the study have been derived largely on a comparable basis, for a broad range of (both light- and heavy-duty) vehicle types and powertrain options and for a range of environmental impacts. This proves the general feasibility of developing a harmonised and systematic LCA across vehicle and powertrain types using the methodological and application approaches developed in this study. Whilst there were differences in the relative performance of powertrains in light- and heavy-duty applications, predominantly due to differences in duty cycle, similar trends were confirmed – i.e. increasing electrification led to increasing benefits versus conventional liquid and also gaseous powertrains, which increased in the medium to long term.

The project has also been successful in implementing a number of novel approaches and enhancements over other previous LCA work in this area. End-of-life (EoL) accounting by applying the PEF Circular Footprint approach better accounts for aspects such as those relating to allocation and material quality. A highly systematic approach was applied to accounting for future changes in the impacts of key materials and energy chains due to decarbonisation of the energy system and process improvement as well as to accounting for the decrease in annual mileage by vehicle age. These novel developments have also allowed the consequences of the methodological choices and key assumptions used in the LCA on environmental impacts to be examined through a wide range of sensitivities. This has helped to highlight potential impact hotspots, areas of uncertainty and areas for potential improvement to be identified.

The results of the analysis generally confirm the ongoing EU policy approach to move to a more circular economy and the initiatives aimed at developing a sustainable value chain for xEV batteries in Europe and driving down industrial emissions. There are also further opportunities to improve existing policy instruments, e.g. related to battery re-use or recycling, as well as finding ways to further incentivise improvements in the operational energy efficiency of powertrains.

The analysis of electricity production chains has provided a robust and comprehensive dataset for a number of regions covering a wide range of generation types. For fuel production chains, this study has highlighted numerous challenges for developing a consistent and harmonised methodology and dataset to evaluate all types of fuel chains through LCA. This has proved difficult in the context of complex methodological considerations and limited data availability for some newer fuel/process types. The results also highlight the importance of methodological choices with regards to the treatment of co-products, as the consistent implementation of a substitution approach shows significant differences, compared to the implementation of an energy allocation approach. Similarly, the inclusion of counterfactual scenarios in the assessment significantly affects the modelling of impacts of secondary fuels. Future research should further explore the modelling of counterfactual scenarios and the building of robust datasets to evaluate them.

Table ES4 provides a summary of the current status for different aspects of the vehicle LCA work performed for this study and recommendations for future work that could expand the coverage or improve the robustness of results and conclusions drawn from these. In addition, the objective of this study was policy LCA analysis, and not to develop an LCA methodology for regulatory purposes (e.g. as requested in the post-2020 CO_2 regulation); some modifications to the methodology and datasets would be necessary to adapt this for such purposes, which are more closely aligned to product LCA.

Table ES4: Summary of the current status for different aspects of the work performed for this study and recommendations for future work

Area	Methods	Data	Recommendation
Areas covered by this study			
Background LCI dataset	🙂	😐 / 🙂	• Review current datasets and assumptions to improve data quality and fill data gaps particularly for carbon fibre reinforced plastic and for secondary and recycled materials • For key materials further consider other potential improvements to material production (e.g. lower impact extraction, improved process efficiencies, alternative processing methods, etc.), material recycling and reduced impacts from secondary materials
Vehicle specification	🙂	🙂	• Further refine current assumptions based on improved data (e.g. on the real-world energy consumption performance of HDVs, particularly for new/alternative powertrain types, sizing/specification of components) • Expand analysis to include other vehicle types (e.g. powered 2-wheelers, other car, van or lorry segments)
Vehicle / battery manufacturing	🙂	🙂	• Improve characterisation of battery manufacturing, particularly for newer and advanced battery chemistries • Gather more information / data on efficiency improvements in recent years and on effects of future improvements
Vehicle operation	🙂	🙂	• Further enhancement to methodologies to better capture sensitivities due to other effects such as climatic impacts on energy consumption and emissions, particularly for HDVs • More detailed examination of the future potential for reductions in regulated operational air quality pollutant emissions (e.g. taking outputs from current EC projects considering potential for post-Euro 6/VI emissions standards) • Further enhancement to the coverage of impacts due to vehicle maintenance, focusing on areas of potential difference between different powertrain/fuel types

Area	Methods	Data	Recommendation
Vehicle / battery End-of-Life			• Improve datasets for certain recycled materials • Further research of end-of-life recycling and battery second life: LCA methodologies and data • Additional sensitivity analysis on how the end-of-life methodology applied impacts on the results (e.g. cut-off vs hybrid vs PEF Circular Footprint)
Electricity production chains			• Update input data on future electricity mix projections • Further review and enhance underlying datasets • Broaden the analysis scope to investigate the potential contributions of required electricity storage on the results
Fuel production chains			• Develop improved foreground data-sets for non-conventional natural gas production, hydrogen production from natural gas, and fuel production processes which are currently at an early stage of commercialisation such as e-fuel production. • Model additional counterfactual and substitution scenarios to provide LCA practitioners with guidance and default values and identify feedstocks or fuel production chains which may be at high risk of causing indirect impacts through their use in fuel production. • Explore the possibility to model all residues as co-products and allocate a share of the impacts of the primary production process to them. • Modelling of additional fuel chains, for example to cover new fuel types (e.g. bio-LPG) or variations on existing fuel chains. • General exploration and improvement to the temporal harmonisation and granularity of data across all areas.
Areas not covered by this study			
Refuelling, recharging, and ERS infrastructure			• Methodologies and datasets need developing to characterise existing and new infrastructure • Fleet-level modelling/assessment may be needed to appropriately allocate impacts on a vehicle-basis
Other infrastructure			• Expansion of boundary to also consider other road infrastructure elements
Modelling of fleet impacts			• Estimation of whole-system/fleet life-cycle impacts using outputs from this study
Effects of new technologies and trends			• Estimation of further operational effects due to new technology or trends: e.g. effects of C-ITS / ITS and autonomous vehicle technologies on (a) production/disposal of new systems added to the vehicle, (b) impacts of infrastructure, (c) impacts on vehicle efficiency / emissions

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Glossary

Abbreviation	Definition
AP	Acidification Potential
AQP	Air Quality Pollutants
B7	7%vol biofuel blend in diesel
BAU	Business As Usual
BEV	Battery Electric Vehicle (fully electric)
BEV-ERS	Battery Electric Vehicle with Electric Road System (i.e. via vehicle pantograph and overhead catenary or other form of dynamic charging)
BSi	British Standards Institute
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DB	Database
EC	European Commission
eLCAr	E-Mobility Life Cycle Assessment Recommendations
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
ETP	Eco-Toxicity Potential
ETS	Emission Trading System
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester (Biodiesel).
FCEV	Fuel Cell Electric Vehicle (running on hydrogen)
FP7	Framework Programme 7
FQD	Fuel Quality Directive (98/70/EC)
GHG	Greenhouse Gases
GWP	Global Warming Potential
GVW	Gross Vehicle Weight
H_2	Hydrogen
HD	Heavy Duty
HDV	Heavy Duty Vehicle (lorries, buses and coaches)
HEV	Hybrid Electric Vehicle
HTP	Human Toxicity Potential
HVO	Hydrotreated Vegetable Oil (Renewable Diesel)
ICE	Internal Combustion Engine

Abbreviation	Definition
ICEV	Internal Combustion Engine Vehicle
ICEV-D	Diesel ICE Vehicle
ISO	International Organisation for Standardisation
kWh	kilo-Watt-Hour
LCA	Life Cycle Assessment
L-cat	L-category Vehicle
LCI	Life Cycle Inventory
LCV	Light Commercial Vehicle (van)
LDV	Light Duty Vehicle (Car or LCV)
LEV	Low Emission Vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
LHV	Lower Heating Value
Li-ion	Lithium Ion
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas.
LR	Long Range
MD	Medium Duty
MDP	Mineral Depletion Potential
MJ	Mega-Joule
MS	Member State
MSW	Municipal Solid Waste.
Mt	Mega ton (million tonnes)
N_2O	Nitrous Oxide
NEDC	New European Drive Cycle
NGO	Non-Government Organisation
NH_3	Ammonia
NOx	Nitrogen Oxides (includes nitrogen monoxide and nitrogen dioxide)
OEM	Original Equipment Manufacturer
PAN	Peroxyacyl Nitrates
PC	Passenger car
PCR	Product Category Rules
PEF	Product Environmental Footprints
PEM	Proton Exchange Membrane
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PIV	Plug-in Vehicle *
PMF	Particulate Matter Formation
PO_4	Phosphate

Abbreviation	Definition
PO_4e	Phosphate equivalent
POCP	Photochemical Ozone Creation Potential
POFP	Photochemical Ozone Formation Potential
PtX	Power-to-X (where X can be a variety of hydrocarbon liquid fuels or gases)
PV	Photo Voltaic
Q&A	Question & Answer
RE	Renewable Energy
RES	Renewable Energy Sources
REEV	Range Extended Electric Vehicle
RFNBO	Renewable Fuel from Non-Biological Origin.
RW	Real world
SD	Single Decker
SETAC	Society of Environmental Toxicology and Chemistry
SMR	Steam Methane Reforming (Hydrogen production from natural gas)
SNG	Synthetic Natural Gas
SO_2	Sulphur Dioxide
SO_2e	Sulphur Dioxide equivalent
SoC	Available State-of-Charge percentage for battery
SOC	Soil Organic Carbon
SR	Short Range
TA	Type Approval
TAP	Total Acidification Potential
TC	Test cycle
TCO	Total Cost of Ownership
TTW	Tank-to-Wheel
V2G	Vehicle-to-Grid
VAT	Value Added Taxes
VOC	Volatile Organic Compound
WHVC	Worldwide Harmonised Vehicle Cycle (for heavy duty vehicles)
WLTC	Worldwide harmonised Light vehicle Test Cycle
WLTP	Worldwide harmonised Light vehicle Test Procedure
WMTC	World Motorcycle Test Cycle
WTT	Well-to-Tank
WTW	Well-to-Wheel
xEV	Electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
ZEV	Zero Emission Vehicle (includes BEV and FCEV)

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Through the course of this study we have received contributions from a range of organisations and individuals through several different means (e.g. informal communications, interviews, Delphi survey, data validation exercise responses and workshops / meetings). We would like to formally acknowledge and thank all the contributors for their insights and for sharing their knowledge with us.

In particular we would like to acknowledge the contribution of Argonne National Laboratory experts to the project, and the valuable material/datasets from their publicly available GREET model and EverBatt battery lifecycle model which were utilised in parts of the application of this project's LCA methodology.

In addition, we thank the IEA for providing information on future improvements to aluminium and steel production that were used to inform our analysis. Our calculation of electricity impacts for non-EU regions are also based on IEA scenario analysis of potential future electricity mix that might be required to meet different GHG reduction objectives.

A full list of contributor organisations from stakeholders can be seen in the table below:

Organisations	
Aachen University	IEA (International Energy Agency)
ACEA (European Automobile Manufacturers' Association)	IFP Energies Novelles
ADAC (German Automobile Club/Association)	IINAS (International Institute for Sustainability Analysis and Strategy)
ADEME (French Environment and Energy Management Agency)	IVL Swedish Environmental Research Institute
AECC (Association for Emissions Control by Catalyst)	JAMA (Japan Automobile Manufacturers Association)
ANL (Argonne National Laboratory)	Joanneum Research
Assogasliquidi/Federchimica	Lanzatech
Audi	LAT (Laboratory of Applied Thermodynamics)
AVERE (European Association for Electromobility)	Life Cycle Analysis for Carbon Capture & Utilisation Working Group
AZC	Life Cycle Associates
BDI	Liquid Gas Europe
BorgWarner	LowCVP
Bosch	Mahle International
BusinessEurope	MAN Truck & Bus
Cerulogy	Mazda
CLEPA (European Association of Automotive Suppliers)	Newcastle University
CNH Industrial	NGVA (Natural & bio Gas Vehicle Association) Europe
CONCAWE	Nissan
Daimler	North Energy
Denso	Northvolt
Detomserve	Novozymes

Organisations	
EBB (European Biodiesel Board)	Now
EBRA (European Battery Recycling Association)	NPL
ECF (European Climate Foundation)	Oeko Institute for Applied Ecology
ecoinvent/EMPA	Paul Scherrer Institut - Laboratory for Energy Systems Analysis
EFOA (European Fuel Oxygenates Association)	PSA Peugeot Citroën
Engie	Recharge - The Advanced Rechargeable & Lithium Batteries Association
ePURE	Renault
Equinor	Saudi Aramco
EREF (European Renewable Energies Federation)	Scania
ERTRAC (European Road Transport Research Advisory Council)	Schaeffler
EURELECTRIC	Subaru
Eurofer (European Steel Association)	Swiss Federal Laboratories for Materials Science and Technology (EMPA), Technology and Society Laboratory
European Aluminium Association	Swiss Federal Office for the Environment (FOEN)
European Council for Automotive R&D - EUCAR	Tesla
Faurecia	thinkstep (Sphera)
FCA (Fiat Chrysler Automobiles)	TNO
FEV	Toyota
FIA (Federation Internationale de l'Automobile)	Transport & Environment
FOEN (Swiss Federal Office for the Environment)	TU Berlin
Ford	TU Graz
Fraunhofer Institute for Structural Durability and System Reliability LBF	UN (United Nations)
French Ministry of Ecology, Sustainable Development and Energy	UPEI
ZF Friedrichshafen	UPM Biofuels
FuelsEurope	VDA (German Association of the Automotive Industry)
GaBi	Volkswagen
Honda	Volvo Cars
Hydrogen Europe	Weber Shandwick
ICCT (International Council on Clean Transportation)	World Auto Steel

1 Introduction and overview

1.1 Introduction

Ricardo Energy & Environment (together with ifeu and E4tech) was commissioned to provide technical support to the European Commission on a *"Pilot study on determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment"* (hereafter, the 'project'). The project was commissioned by the European Commission's DG Climate Action (hereafter 'the EC').

This final report provides:

- An overview of the evidence and data collection approach that informed the development and application of the life cycle assessment (LCA) methodology (Section 2).
- A summary of the LCA methodology developed for this study (Section 3).
- An overview of the framework for the application of the methodology, including the selection criteria for displaying results (Section 4).
- The main results from the application of the methodology for each stage of the lifecycle and for the vehicle as a whole, including sensitivities on key assumptions of the methodology (Section 5).
- Summary of the key conclusions and recommendations from the study (Section 6).

1.2 Background and Context

The EU has set objectives and established a comprehensive legal framework to address air pollution, climate change and other environmental issues. In the transport sector, a number of EU-level policies have been put in place to tackle sectoral environmental impacts and support the transition towards a low-carbon, circular economy. Road transport, in particular, is responsible for a range of environmental impacts which are addressed by EU policies.

To inform decision-making, it is paramount to develop a better understanding of the environmental impacts of road vehicles over their *entire* lifecycle. Traditionally, the use phase has accounted for the most significant proportion of overall vehicle lifecycle impacts, but lower emission fuels, improved emissions control, and alternative drivetrains (in particular electric vehicles) point to the relevance of assessing environmental impacts in the other life stages.

Life cycle assessment (LCA) enables comparison of different vehicle technologies, including fuel options, on a like-for-like basis. An LCA can help identify key impacts and hotspots throughout the different life cycle stages, in order to better understand the range of opportunities to reduce them, as well as mitigate any potential burden shifting. At the same time, assumptions made are inevitably either context-specific or averaged to cover a broader scope for analysis. Ultimately the development of an LCA approach to road vehicles will help support evidence-based decision-making that enhances synergies and ensures overall reductions in environmental impacts across the vehicle lifecycle.

LCA modelling of vehicles is complex and requires methodological choices, which entail important variations in results. Whilst a range of other studies have developed methodologies to do this, their coverage has mostly been much narrower, thus not been complete in tackling all the areas of interest for this study in a consistent and sufficiently detailed way and/or for the EU-specific context.

The EC therefore commissioned this study to look into the environmental impacts of road vehicles in a holistic manner, using an LCA approach covering the manufacturing, use and end-of-life phases of selected vehicle categories, and taking into account the energy/fuel expected to be in use at time horizon 2050. A key objective of this study is to combine past knowledge from the literature, as well as the knowledge and expertise from the project team and stakeholders to propose a comprehensive methodology filling past data and methodological gaps, as well as developing and applying more novel aspects to further enhance the analysis.

The goal of this study was not to assess the possibility of developing methodologies for reporting the life cycle CO_2 emissions of all new vehicles as the Commission is requested to do under the LDV and HDV CO_2 Regulations (EU) 2019/631 and (EU) 2019/1242, respectively). A high-level discussion of this issue is provided in Appendix A6 of this document.

The methodological choices made in this study, including the specific modelling of environmental impacts and use of datasets, were primarily based on available datasets and literature. The breadth of the study did not allow for a consistent level of robustness and validation of all data, which, in several instances, were limited (especially for certain energy/fuel chains). The study outcomes primarily intend to show the consequences of methodological choices and key assumptions used in LCA on the resulting environmental impacts of vehicle and energy chains, and to identify potential hotspots and areas of uncertainty and potential future improvement. With due regards to the novel nature of some of these methodological choices and the limited robustness underlying some of the data used in this study for certain fuel production chains, it is important to take the results of this study with caution to avoid any definitive judgement on the environmental impacts in absolute and relative terms in these areas. Nevertheless, the outputs from this study *do* provide robust indications on relative performance of the different options particularly for vehicle powertrain comparisons, electricity chains, and conventional fuels, and on how temporal and spatial considerations (e.g. due to variations in electricity mix) lead to different situations and potential future developments likely to affect these comparisons.

1.3 Introduction to life cycle assessment (LCA)

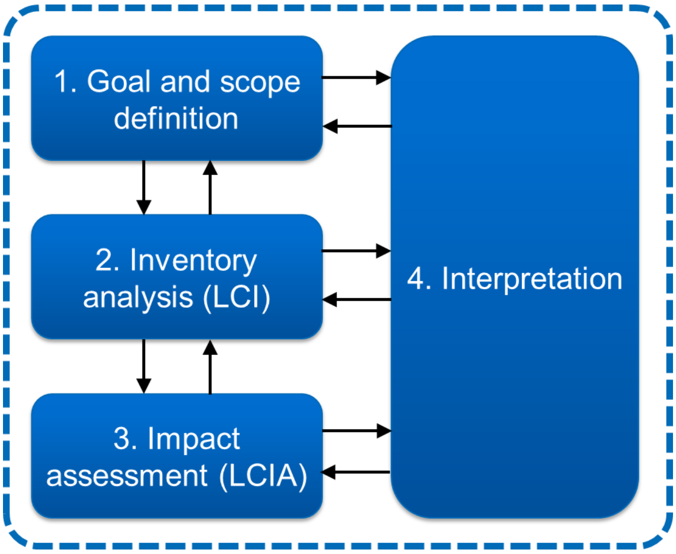
Life cycle assessments as an instrument of environmental analysis have been established since the 1980s. The LCA approach represents an important method for the characterisation and identification of environmental burdens of systems. To date, it is the sole instrument for environmental assessments standardised with a global ISO standard.

The **ISO 14040/144044** (ISO14040, 2006) (ISO14044, 2006) norms provide the common basis for all LCA studies today in the form of a standard. They include general requirements for all aspects of a products' lifecycle. However, due to the broad scopes of LCA studies today the ISO norms still leave many methodological aspects to be further defined by the LCA practitioner.

In practice life cycle assessment is a fit-for-purpose procedure to record and evaluate environmentally relevant processes. Originally developed primarily to evaluate products, it is now also used for processes, services and behaviour. The results of LCAs can be used to optimise processes for sustainable production, but also for policy development. Depending on the time horizon (current or future situation) different modelling approaches can be taken. The key strength of an LCA lies in the fact that all stages of the product or process life cycle are taken into consideration. If the analysis focused on a single process stage or a subsection of the product life cycle (e.g. only the use phase of the vehicle), grave misinterpretation of environmental impacts, e.g. from the supply of mobility as a service, may be the consequence.

The main principles of an LCA are therefore (1) all relevant potential harmful effects on the environmental media soil, air and water must be taken into account and (2) all material flows associated with the system under consideration (raw material inputs and emissions from supply and disposal processes, energy generation, transport and other processes) must be taken into account. The LCA framework set out in the standards is summarised in Figure 1.1, which is followed by a description of each stage.

Figure 1.1: The four stages of LCA (ISO 14040)



Goal and Scope Definition	In the first phase, the goal, scope, and boundary of the project are formally defined and documented. This phase is absolutely critical to producing a fit-for-purpose study, and involves agreement on a number of subjects (Table 1.1)
Inventory Analysis (LCI)	The project life cycle inventory (LCI) can then be developed. This lists: • all the raw materials that make up the functional unit (identity and weight). • all the energy inputs (identity and amount). • all the by-products and wastes, with their management fate (recycled, landfilled, etc.). • all emissions to land, water and air. As well as collating a mass and energy balance for the system, the analysis needs to map those "flows" against what is available in the chosen LCA software package, including the opportunity of building and computing new pathways/chains.
Impact Assessment (LCIA)	In this stage the impacts of each item in the inventory are assessed using the environmental indicators (global warming, etc.) identified during the scoping stage. The inventory analysis and chosen sets of emissions factors are combined to reveal the overall impacts
Interpretation	interpretation takes place throughout the LCA process in an ISO-compliant study. Even in the simplest projects, the practitioner should examine the LCIA and explore the key drivers for the results. This may lead to iterations of the calculations, particularly looking at the sensitivity of the results to various perturbations in the input data. The results of the LCA should be written up in a final LCA report.

The methodological choices applied within an LCA need to be appropriate for the goal and scope of the analysis and should be defined at the very start of the project (see chapter 3.1 for this study) in the goal and scope definition. Key choices which needed to be made are summarised in Table 1.1. The approach used for each in this study is given in chapter 3.

Table 1.1: Key methodological choices in LCA

Aspect	Considerations
Functional Unit	According to (ISO14040, 2006), "*LCA is a relative approach, which is structured around a functional unit*". The **functional unit** represents the reference product or service to which the input and output flows from the life cycle inventory are related. Due to the comparative character of many LCA's the functional unit plays a critical role and must clearly define the functions (performance characteristics) of the system

Aspect	Considerations
	under investigation. The functional unit also determines the comparability of different studies.
Scope	The Scope (also known as **System Boundary**) determines which processes are included in the assessment and needs to be in accordance with the goal of the study. Since results from LCA studies can be influenced by selecting favourable, erroneous or incomplete system boundaries, they need to be clearly defined at the start of the project and include all relevant processes. In the process of defining the system boundaries, cut-off criteria can be used to reduce complexity of the modelling process. **Cut-off criteria** usually specify a minimum contribution to environmental impacts or an amount of material or energy flow to justify an exclusion from the system. By doing this, it is ensured that all relevant contributions to the product system are assessed while limiting the overall complexity of the analysed system to a manageable level. Sometimes also availability of data to perform the study may be taken into account. Nevertheless, any omissions need to be clearly stated and justified within the study.
Modelling approach	There are two different general LCA modelling approaches. **Attributional LCA** means that the inputs and outputs of a system are attributed to the functional unit by partitioning the unit process according to a normative rule. Generally, attributional LCA is well suited for products that are already offered on the market and where changes in production do not result in any large-scale consequences. When decisions are being analysed that may result in large scale changes of an entire system, a **consequential LCA** approach might be needed. In a consequential LCA, activities are linked to include all aspects that are expected to change as a consequence of a demand for the specific product in a system.
Multi-functionality	The modelling approach is also related to multi-functionality. If a process yields more than one product (e.g. in a co-production or when recycling or waste- processing is done), this process is a multi-functional process. A three-step procedure/hierarchy for dealing with multi-functionality is described in (ISO14040, 2006) and summarised below: • **Subdivision** of the product system is described as the preferred option. Here a multifunctional black box unit process is subdivided into mono-functional single operation unit processes thereby cutting free the required process and avoiding the need for allocation/ substitution. • When this is not possible, a **system expansion** (expanding the system to include the function of the co-product) or substitution (credit for the supplied co-product) is done. • Thirdly, an **allocation** according to preferably physical or other parameters of the co-products is possible. When doing an allocation, different physical properties of a product may be used (e.g. an exergetic allocation is common for energy resources). When no physical relationships can be observed, an economic allocation may also be feasible.
Vehicle end-of-life (EoL)	The question of the modelling approach and multi-functionality is also closely linked to end-of-life treatment. One possibility to handle recycling is to have a **closed-loop** recycling. This is often not usable in reality, since a downgrading of the recycled materials and a time lag between primary and secondary use occurs. Therefore, other approaches are often applied of which the most common options are: • **Avoided-burden approach (0:100)** (also referred to as “End-of-Life” approach): The secondary material may (partially) substitute a primary material, which results in a credit for the recycling process. • **Cut-off approach (100:0)** (also referred to as “recycled content” approach): A cut-off between the primary and secondary system is performed. Here, the primary user receives the full burdens for the waste treatment, but no burdens for

Aspect	Considerations
	recycling. No credit for recycling or waste treatment of by-products is given and a simple cut-off is performed. If the primary and secondary user of a material is known, a **50:50** approach may also be taken**.** Here all environmental impacts are shared between the two products systems, so that each gets 50% of those. Another possibility is to perform an allocation between the primary and secondary usages of a material. This method is closely linked to the ecoinvent database and is used in its system model "**allocation at the point of substitution**" (APOS). These approaches, however, have a lower relevance in LCA practice today.
Environmental impacts	Life-cycle inventories (LCIs) often operate with thousands of substances. Some of these substances are understandable and instructive as such e.g. CO_2 emissions or particulate matter and NOx emissions in assessments of transport. Nevertheless, due to the large amount of substances frequently included in LCIs, **impact categories** are commonly used to enhance understanding and evaluate the magnitude and significance of the potential environmental impacts caused by a product. Thus, the inventory data is grouped and weighted according to potential damages. The choice of which environmental impacts to study is critical to an LCA report, and should be made during the scoping phase. Two types of indicators are generally distinguished. **Endpoint indicators** directly refer to an impact in the field of human health, natural environment or resource consumption and most closely reflect the protected good. A common example is the assessment of life-years lost in respect to human health (e.g. DALYs (disability adjusted life years lost)). **Midpoint indicators** are weighting substances with similar effects along their mechanisms into an impact indicator via characterization factors. The impacts, however, may affect different endpoints (e.g. human health AND natural environment). It is important to understand that midpoint indicators only aggregate potential impacts and thus do not quantify actual end point damages, which also depend on other factors such as location-based/situational aspects, e.g. exposure levels for toxicity impacts.
Primary vs secondary data:	The last consideration concerns what data source(s) will be used – primary or secondary. "Primary data" come from the actual operations under investigation, whereas "secondary (or proxy) data" come from literature and databases. Clearly, primary data are preferable, but their use relies both on the data being available and on suitable funds being available. Frequently, the goal of the study can be achieved without needing to collect primary data. Sometimes, organisations initially use secondary data to develop an overall picture of the system impacts (screening), and then iterate with primary data wherever the key drivers and/or impacts are identified.

At this point it is helpful to consider how different choices are made depending on the type of LCA study that is being conducted. For this study the goal was to aid policy analysis. However, in case the objective would be to develop methodologies suitable for reporting the life cycle CO_2 emissions of all new vehicles this would require an approach more aligned with a product LCA, where some methodological choices or data may be different - a further discussion is provided in Appendix A6 of this report. A summary of the main differences between 'Policy LCA' studies and 'Product LCA' studies is presented in the following Table 1.2, which are also discussed further in the literature review summary Section 2.2.4.1.

Table 1.2: Comparison between LCA for policy analysis and LCA for product environmental reporting

LCA Type	Audience and objective	Key differences between policy and product LCA
Policy Analysis	• **Primary intended audience** are policy-makers and academics • **Purpose** is to aid understanding of potential wider societal implications for policy development • **Impact** of product/service **within wider social system** • Subject may be **real or hypothetical/generic**	• **Wider** scope/boundaries with a more exploratory approach on method (e.g. on fuel chains) or datasets to enhance understanding on influence • **Generic** vehicle/powertrain types designed to be broadly equivalent/similar to aid comparison • Significant consideration of both **temporal** and **spatial** effects, e.g. linked to EC modelling scenarios • Wide variety of **impacts**, **sensitivities** to explore variation in key assumptions and uncertainties
Product Environmental Reporting	• **Intended audience** is customers and general public • **Purpose** is the quantification of impacts of manufacturer's **specific products** • **Certified** to conform to LCA standards, e.g. ISO, PEF • Results usually in Environmental Product Declarations (EPDs) or Corporate Responsibility Reports	• General LCA methods *may* be similar to policy LCA (likely with a tighter focus/boundary); usually align with regulation for fuels and electricity impacts ○ E.g. standard WTW **regulatory** defaults/average • Datasets for vehicles based on **manufacturer** / supply-chain data for **specific models**, and using also information from **type approval** • **GWP** (i.e. GHG) impacts at least, possibly others (e.g. cumulative energy, regulated pollutants) • Likely limited inclusion of temporal effects

1.4 Scope and objectives, overview of project methodology

The aim of this study is to improve the understanding of the environmental impacts of road vehicles and the methodologies to assess them in the mid- to long-term timeframe (2020 to 2050). It covers light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) with different types of powertrains (internal combustion engine and/or electric engine powered by fuel cells or batteries) and using different types of energy (of fossil and/or renewable origin).

It has two main objectives:

1. To develop a methodological approach for an LCA of road vehicles (including the fuels/energy), using a combination of state-of-the art vehicle LCA as well as novel methodological choices, based on a literature review and stakeholder consultation.
2. To apply this approach to compare the outcomes for selected vehicle categories expected to be in use over the time period of 2020 to 2050.

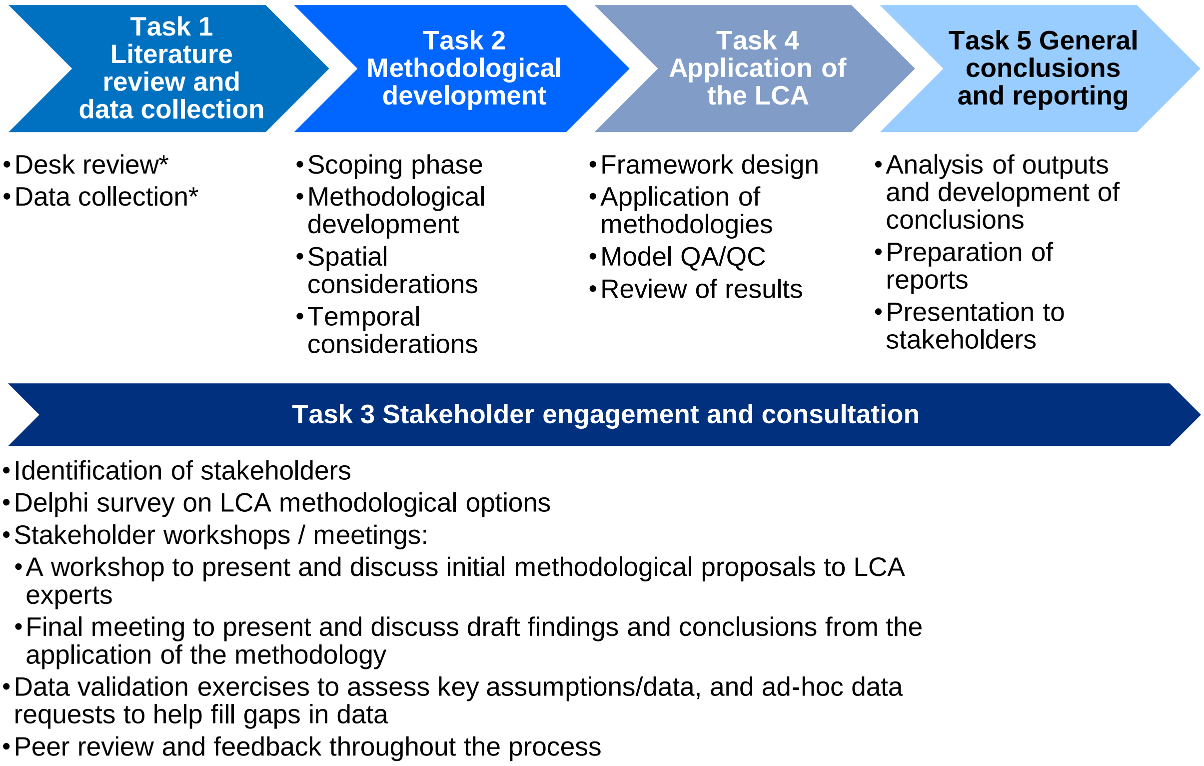
The study aims, in particular, to help answer the questions in Table 1.3.

Table 1.3: Key research questions in the study

Study areas	Research questions
Development of a LCA methodology	1. Which LCA approaches (or partial analyses) have been used so far and for which purpose/audience (regulatory, consumer information, etc.)? How do they relate to the principles, requirements and guidelines set out in the EN ISO 14040 and 14044 standards? 2. What is the state of knowledge on LCA of LDVs and HDVs, taking into account the fuel types they could use? What are the main existing data gaps? 3. What are the most appropriate and coherent LCA methodologies to objectively assess GHG emissions and other main environmental impacts associated with LDVs and HDVs (to be registered over the period 2020 to 2050), taking into account the trade-off between accuracy and feasibility?
Application of the LCA methodology	4. What are the consequences of LCA methodological choices on how different vehicle types (combinations of powertrains and fuel types) compare to each other in terms of GHG emissions and other main environmental impacts? 5. How do these methodological choices affect the modelling of environmental impacts over time (i.e. between 2020 and 2050), taking into account existing and future policies regarding GHG and air pollutant emissions (in the EU and third countries), raw materials and manufacturing processes for the vehicles and their components (especially batteries), etc.?
General conclusions	6. What are the key factors determining GHG emissions and other LCA impacts over the life cycle of different vehicles? 7. How could those factors be affected by policies in order to lower those impacts? 8. What are the pros and cons of some of the novel methodological approaches implemented in this study? What additional research would be required to increase the robustness of the results?

A summary of the overall project structure is provided in Figure 1.2, with the goal and scope defined for the work discussed in more detail in Section 3.1.1 on the LCA methodology development. The study began with a comprehensive literature review which is described in Section 2; Findings from the literature review, in tandem with input from stakeholder consultation (also described in Section 2), were used to develop an appropriate LCA methodology, as set out in Section 3. Section 4 describes how the methodology was applied in practice and results are presented and discussed in Section 5. Section 6 summarises the key conclusions and recommendations from the study. Finally, the references are provided in Section 7, with additional detail from across all project tasks provided in the Appendices.

Figure 1.2: Overview of the project methodology



Notes: * The literature review and data collection task included the following elements:

- Development of search criteria to identify key literature/evidence and the development of a rapid evidence assessment (REA) framework to efficiently assess and extract key information
- Identification, review and synthesis of evidence; identification of environmental hotspots and key gaps in knowledge or data

2 Review of evidence and data: literature review, data collection and consultation

2.1 Overview

The development and application of the LCA methodology was informed by evidence and data collected throughout the course of the study, based on two main research tools: literature review and stakeholder consultation. The objectives and activities organised for these two main tools are outlined in Table 2.1.

Table 2.1: Overview of main research tools used in this study

Research tool	Objectives	Activities
Literature review	An extensive review of the literature on LCA of vehicles, key components and transport energy carriers was undertaken to support the development of proposals for the LCA methodology and collect key data to feed into the application of the methodology	Desk research Rapid Evidence Assessment (REA) Data requests
Stakeholder consultation	A range of stakeholder consultation activities were organised to support the development of the methodology, fill data gaps and validate key assumptions for the application of the methodology	Delphi Survey Workshops Data validation exercises Data requests

2.2 Summary of literature review

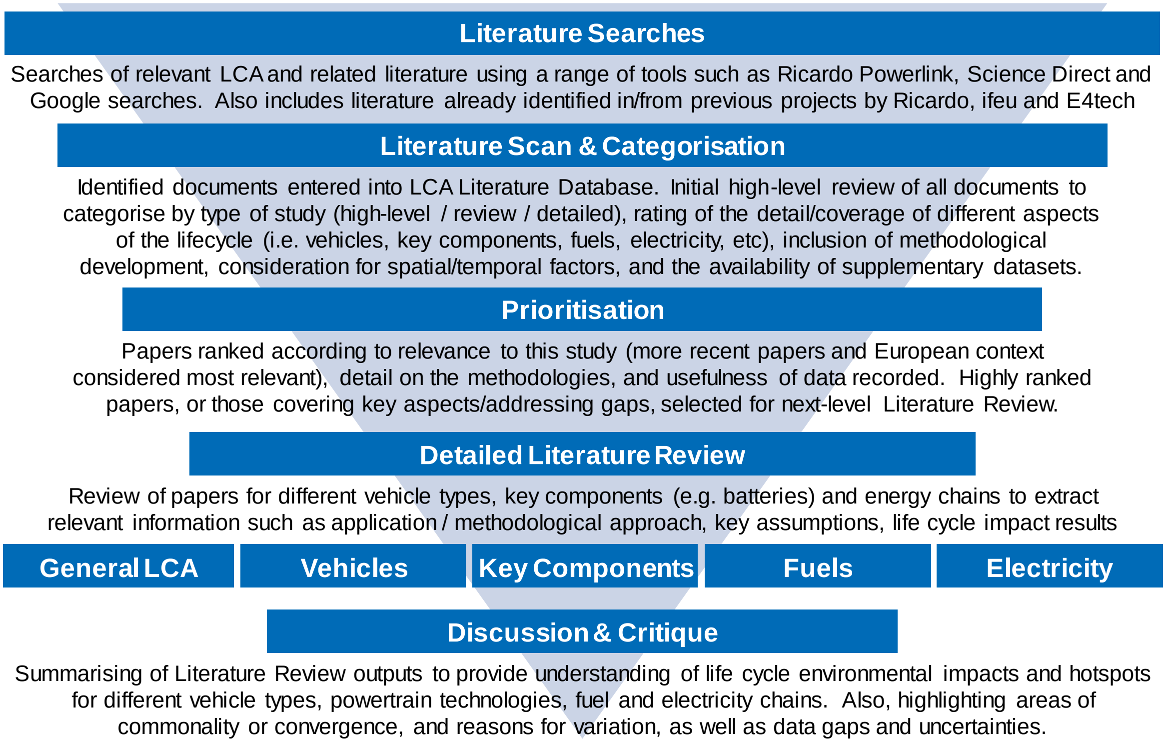
2.2.1 Overall approach

The literature review for this study was based on a Rapid Evidence Assessment (REA) methodology to provide a rigorous analysis and synthesis of the evidence available from published literature. Key objectives were to gain an understanding of the relevant life cycle environmental impacts for different vehicle types, powertrain technologies and energy sources, and to identify significant differences and strengths of previous work to inform the development of a suitable methodological approach for this study.

The literature review process is summarised in Figure 2.1. The first step was the identification and collation of relevant documents; this was done using a range of tools such as Ricardo PowerLink, Science Direct and Google searches. Literature previously identified for previous work (e.g. for JRC (Ricardo Energy & Environment, 2019), and LowCVP (Ricardo, 2018)) was also included. The identified documents included different types of LCA studies (detailed, high-level or reviews) as well as studies covering the vehicle or key components, and lifecycle and energy chains for the different powertrains, vehicle types and energy sources considered in this study. Literature that discusses future implications and regional variability as well as those that provided supplementary datasets were also included. In total, 347 papers and reports were identified.

An initial pre-screening was then applied, recording key information from the documents in a database to help prioritise literature for a more detailed review in the next stage, and to identify key gaps. Literature was prioritised on the basis of the usefulness of its content and for the project, and these priority studies were then reviewed in detail, with further information captured in order to inform the methodological choices required in the study. The findings from this review are summarised below and presented in more detail in Appendix A1.

Figure 2.1: Overview of the literature review process



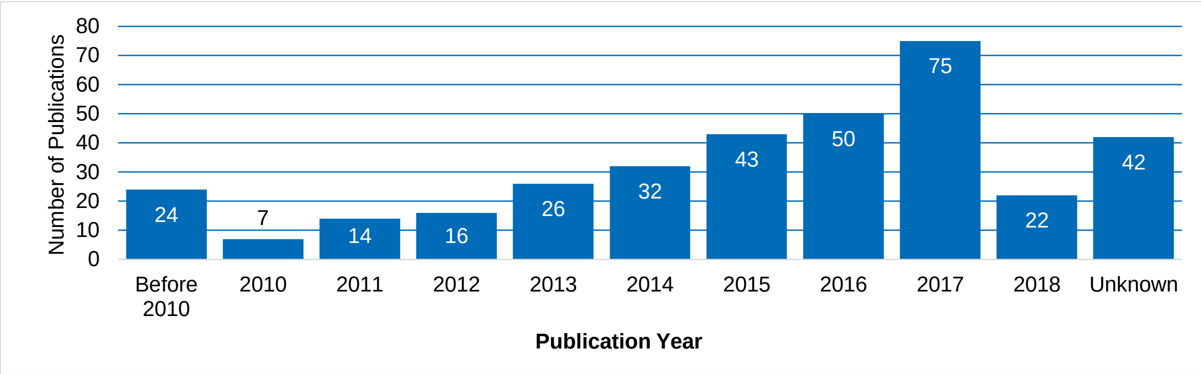
2.2.2 Summary of literature coverage

Basic information was collected for all 347 documents identified. This included logging whether the document covered certain topic areas, and in how much detail. For those that were shortlisted for a more detailed review, further information was captured on vehicle types, regional coverage, powertrain and fuel types, environmental impact categories and lifecycle stages assessed.

The literature review prioritised papers published in recent years as shown in Figure 2.2. Regarding the types of studies captured, the majority (228) of publications in the literature database were categorised as LCAs. There were an additional 114 publications that, while not being an LCA themselves, contained information or data useful to an LCA. For instance, this could be a Europe-wide study on driving patterns, annual and lifetime mileage of different vehicle segments (Ricardo-AEA, 2014), a car manufacturers sustainability strategy that includes future mechanical changes and effects on emissions (BMW, 2015) or an academic study focused on current and future recycling process options for electric vehicle batteries (Gaines, 2014).

Considering the four broad areas of interest for this study, i.e., the vehicle, key components (e.g. battery for an EV), electricity or H_2 chain and other fuel chains (e.g. fossil fuels), over 100 publications have been identified that cover at least one of the areas. In terms of the level of detail provided by these studies, all but electricity/H_2 chain have over 45 papers with a very detailed focus. In addition, across all papers in the literature database, 82 of the reports were found to have supplementary materials containing very detailed datasets, 105 had some form of dataset.

Figure 2.2: Publications by Year

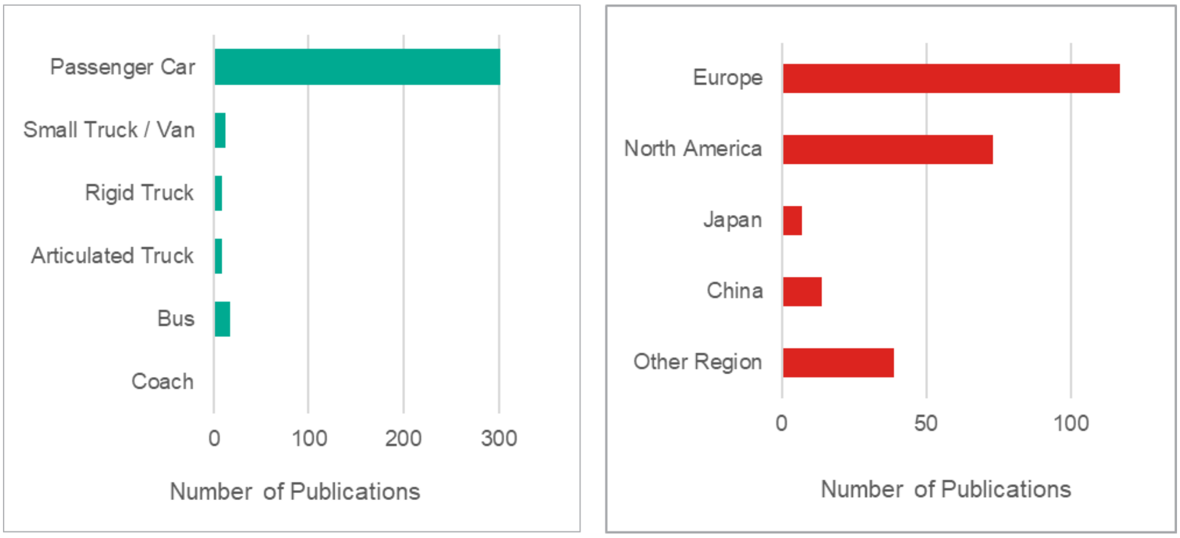


2.2.2.1 Vehicle types and regional coverage

Passenger cars attract significantly greater attention than other vehicle types in the papers and reports covered in the literature database. As shown in Figure 2.3, they feature in just over 300 (87%) of the publications, whereas the other vehicles types all appear in less than 5%. As the literature search focused on a range of vehicles, including passenger cars, trucks and buses with conventional gasoline and diesel ICE, hybrid, and electric vehicle technologies, it is thought that this represents a bias in wider research focus. At least one paper has been reviewed for all vehicle types in scope, except for coaches (/long distance buses), where no examples were identified.

Figure 2.3 below also shows the geographical coverage of the literature sources. As the graph shows, the literature database is dominated by papers and reports from Europe and North America. Additionally, 16 of these papers included multiple regions[4] and 25 had some degree of global coverage.

Figure 2.3: Publication by (a) vehicle type and (b) region



(a) Vehicle Type **(b) Region**

2.2.2.2 Powertrain and fuel type

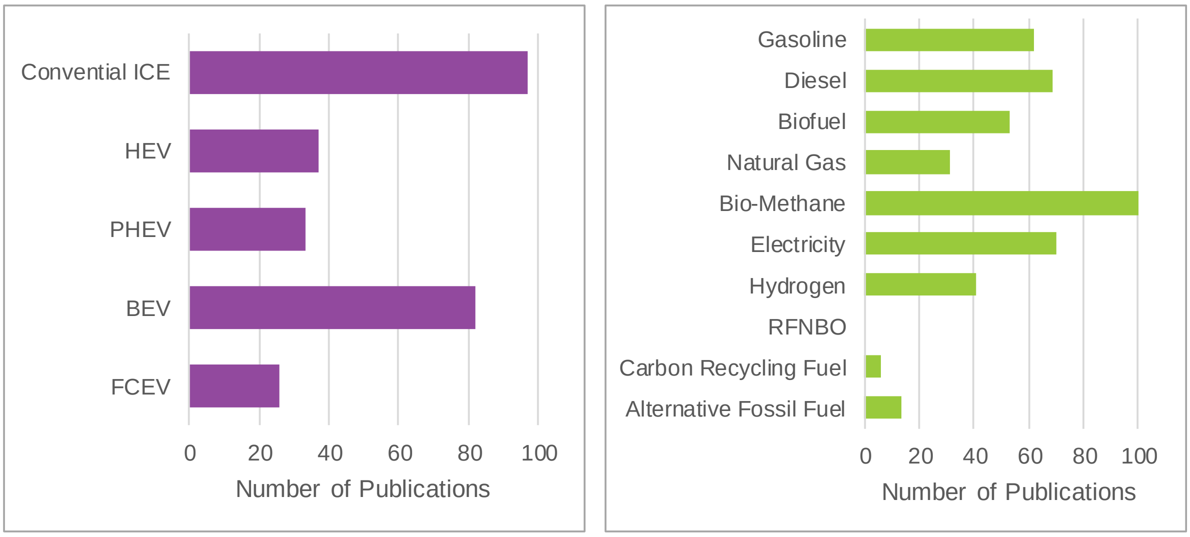
Figure 2.4 shows the number of publications that cover various powertrain types of interest. Conventional ICEV (Internal Combustion Engine Vehicle, including diesel and gasoline) are the most frequently (28%) covered. BEV (Battery Electric Vehicle) appear in 24%, and PHEV (Plug-in Hybrid Electric Vehicle), HEV (Hybrid Electric Vehicle) and FCEV (Fuel Cell Electric Vehicle) have similar levels of coverage, with FCEV having the lowest coverage, with only 8% of papers.

[4] Others included comparisons between multiple geographic locations, from within the same region.

A range of fuel types were also covered in the literature identified and reviewed. Conventional vehicle fuels and established alternative fuels are well covered in the database as shown in Figure 2.4. Biomethane, carbon recycling fuels and alternative fossil fuels have a comparatively low coverage.

It is important to note that these figures do not directly correspond to LCA covering the relevant powertrains they are associated with, as many (e.g. well-to-tank, WTT) studies purely focus on the fuel type (e.g. a number of papers were included that focused purely on the hydrogen production cycle). Equally, literature conducting cradle-to-gate analysis of vehicles (e.g. tank-to-wheels, TTW) did not cover fuel cycles.

Figure 2.4: Publications by (a) Powertrain Type, and (b) Fuel Type



(a) Powertrain Type **(b) Fuel Type**

2.2.2.3 Environmental impact categories and lifecycle stages

Table 2.2 shows the environmental impact categories consistently found in the literature analysed, and Figure 2.5 shows the coverage of specific LCA impact categories. Appearing in 63% publications, GWP is the most common impact discussed, however this impact is global/not context specific, and many of the other impacts from transport are more location specific. Moreover, a number of these analyse the GWP without considering further impact categories. Land use change and water consumption are covered in the fewest papers, each only representing around 4% papers.

Overall, few LCA studies explicitly provide a justification for the impact categories they assess. In addition, the choice of categories (either explicitly or implicitly justified) appear to be based on the impacts assessed by previous studies (to allow comparisons) and/or expert judgment on which impacts are most relevant for vehicle lifecycle (i.e. those impacts for which the vehicle is expected to contribute the most).

In particular, the dominance of GWP in LCA studies seems to be in part due to higher awareness of this environmental impact and more widespread understanding of the associated methodologies. As discussed in section 2.2.3.1, this impact category is also more important, in relative terms, for the road transport sector. It has therefore been the focus for many studies assessing the ability of different powertrain or fuel types to contribute to GHG reduction objectives.

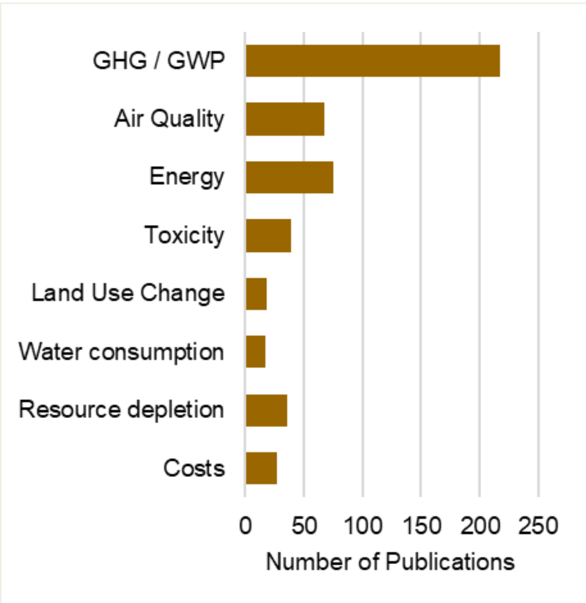
All stages of the lifecycle were covered by literature in the database, as shown in Figure 2.5. Well-to-wheel[5] is the most common stage covered, as it appears in 38% of publications. Infrastructure, which could cover charging points for BEV or refuelling pumps for ICEV and FCEV, garners the least focus in papers, featuring in 4%.

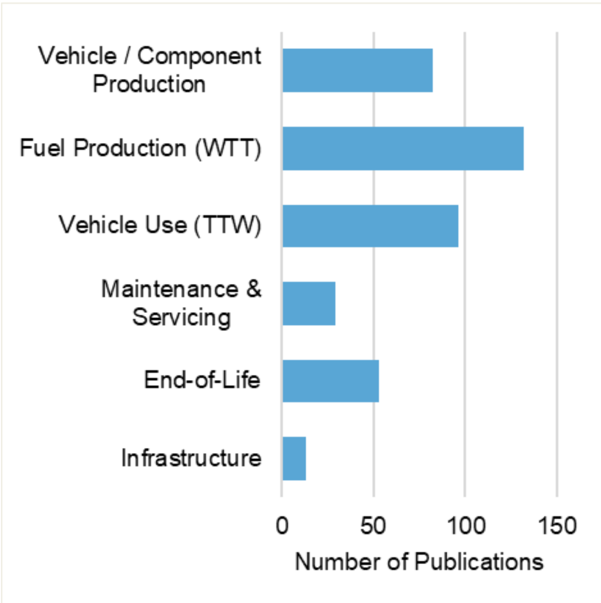
[5] WTW study covers the impacts from production and use of the fuel/electricity in a vehicle, but not other wider impacts due to the vehicle itself, and usually disregarding minor impacts (e.g. fuel conversion plant annualised over its productive life). By definition, an LCA will usually include the complete WTW stage (comprising well-to-tank – WTT, and tank-to-wheel – TTW components) in addition to the vehicle production and end-of-life stages of the vehicle lifecycle. See Figure 3.1 for more details.

Table 2.2: Impacts areas and mid-point categories covered by the literature

Impact area	Details
Global Warming Potential (GWP) / GHG	GWP is an index to measure the contribution to global warming of a substance that is released into the atmosphere. GWP is impacted mainly by the emission of greenhouse gases (GHG) and is measured in CO_2 equivalents.
Air Quality	Factors affecting air quality that are commonly discussed include: Acidification Potential (AP), Particulate Matter Formation Potential (PMFP), Photochemical Ozone Formation Potential (POFP).
Energy	Typically, a Cumulative Energy Demand (CED) (also known as primary energy demand) approach employed, which includes direct and indirect energy use throughout the entire life cycle. There are also sub-categories of non-renewable cumulative energy demand (NRCED), fossil energy use (FEU), primary fossil energy use (PFEU), and secondary energy use (SEU).
Toxicity and aquatic impacts	Includes human toxicity potential (HTP), water and terrestrial eco-toxicity potential (ETP), eutrophication potential (EP), ionizing radiation (IR).
Land use change	Land Use Change (LUC) and Indirect Land Use Change (ILUC): regards an activity's transformation of land from one purpose to another by human activity
Water consumption	The volume of fresh water required
Resource depletion	A vehicle requires numerous resources during its lifetime. Depletion specifically refers to the consumption of a resource faster than it can be replenished. Abiotic Resource Depletion Potential (ADP) is a typical LCA impact factor used that covers this aspect. The key resources affected in a vehicle life-cycle include: fossil energy depletion, metal and mineral depletion.
Costs	Total Cost of Ownership (TCO) can be considered as a form of life-cycle analysis that covers the direct financial costs of ownership of a vehicle (i.e., costs associated with the different stages of the vehicle lifecycle). In addition, there is an economic cost associated with environmental impacts; some studies also include the monetization of health and environmental effects to explain this.

Figure 2.5: Publications by (a) Life Cycle Impact category, and (b) Life Cycle Stages included in Analysis

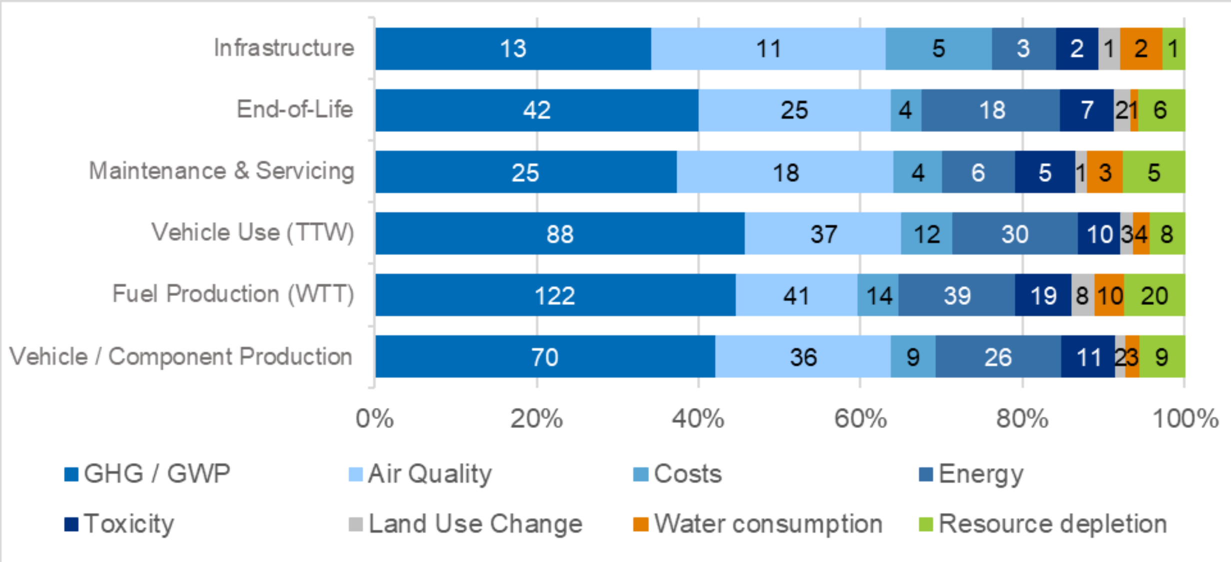




(a) Life Cycle Impact Category **(b) Life Cycle Stages included in the analysis**

Figure 2.6 cross references publications containing each LCA stage with each environmental impact category, in order to identify any data gaps. As the graph shows, every life cycle stage has at least one paper for the environmental impact categories. GWP has the highest coverage, with consistently high proportions of papers analysing this environmental impact at each life cycle stage. Both infrastructure and maintenance and servicing, on the other hand, have consistently low numbers. This is particularly true of papers focusing on toxicity, land-use change, resource depletion and water consumption. Additionally, infrastructure has little coverage of the energy impacts.

Figure 2.6: Publications by LCA stages vs Environmental Impacts



2.2.3 Conclusions from the literature findings and the importance of key parameters / assumptions

Detailed assessment of some of the studies presented above shows that there is significant variability in the results reported (due to differences in data sources and model). However, it is still possible to derive conclusions regarding the contribution of life cycle stages and the relative environmental burden of different types of vehicle, powertrain and energy. Key points are discussed below and a more complete overview of the findings in this section is provided in Appendix A1.

As noted above, there is a strong focus of the literature on certain impact categories (with GHG emissions or GWP being the most common), vehicle types (passenger cars dominate) and more conventional fuel/energy type (e.g. petrol, diesel, electricity). This should be taken into consideration in the discussion presented here, where more focus is given to these, although we have attempted to highlight areas of similarity and difference with other impact categories, vehicle types and energy sources, based on the more limited range of literature/information available.

2.2.3.1 Importance of different environmental impacts

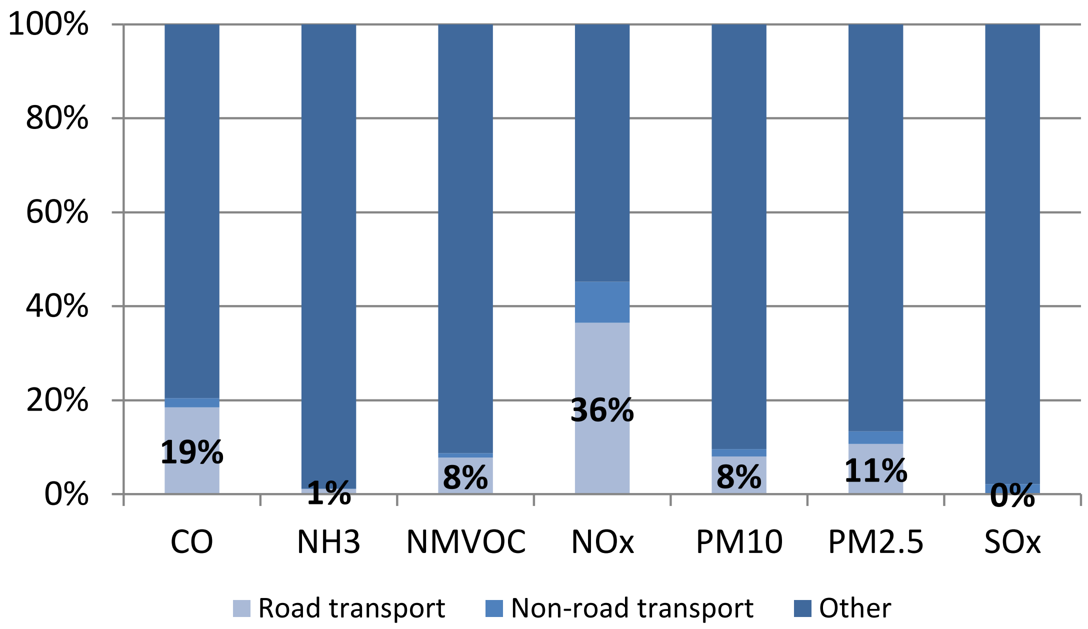
Greenhouse gas emissions can be identified as a highly relevant impact category for road transport vehicles. Transport in general remains one of the larger emitters of greenhouse gas emissions in the EU with a total share of 27 % and a share of 22% if international aviation and maritime emissions are excluded (European Environment Agency, 2020). These emissions are closely related to final energy consumption in the use phase: transport had a share of 30 % on EU total final energy consumption in 2017 of which 93 % was due to fossil fuels (European Environment Agency, 2020).

Road transport is also a significant source of several important air pollutants as Figure 2.7 illustrates. The relative weighting given to each of these common air pollutants in the environmental impact categories and impact assessment methodologies used in this study is also summarised in Table 2.3. Together, the figure and table show the significance/importance of road transport NOx emissions in influencing a range of different mid-point impact categories. Foremost, road transport is still responsible for almost 36% of European NOx emissions, which contribute to the mid-point impacts of Acidification and Eutrophication Potential, Photochemical Ozone Creation Potential (POCP) and particulate matter formation (PMF). Also, the road transport share of total CO emissions, which contribute to POCP, is about 19%.

Furthermore, road transport is responsible for 11% of $PM_{2.5}$ emissions which contribute to particulate matter formation. Both can therefore be regarded as relevant for the assessment of transport impacts. Also emissions of non-methane volatile organic compounds from road transport are significant (8% contribution to total emissions) and contribute to POCP and particulate matter formation.

Ammonia (NH_3), which contributes to Acidification, Eutrophication and particulate matter formation, is not caused by transport directly, but largely by agriculture (92% of NH3 emissions according to (EEA, 2020)) which might have implications for bioenergy.

Figure 2.7: Contribution of road transport to major air pollutants in the EU 2017



Source: (EEA, 2020a)

Table 2.3: Weighting factors for selected impact categories

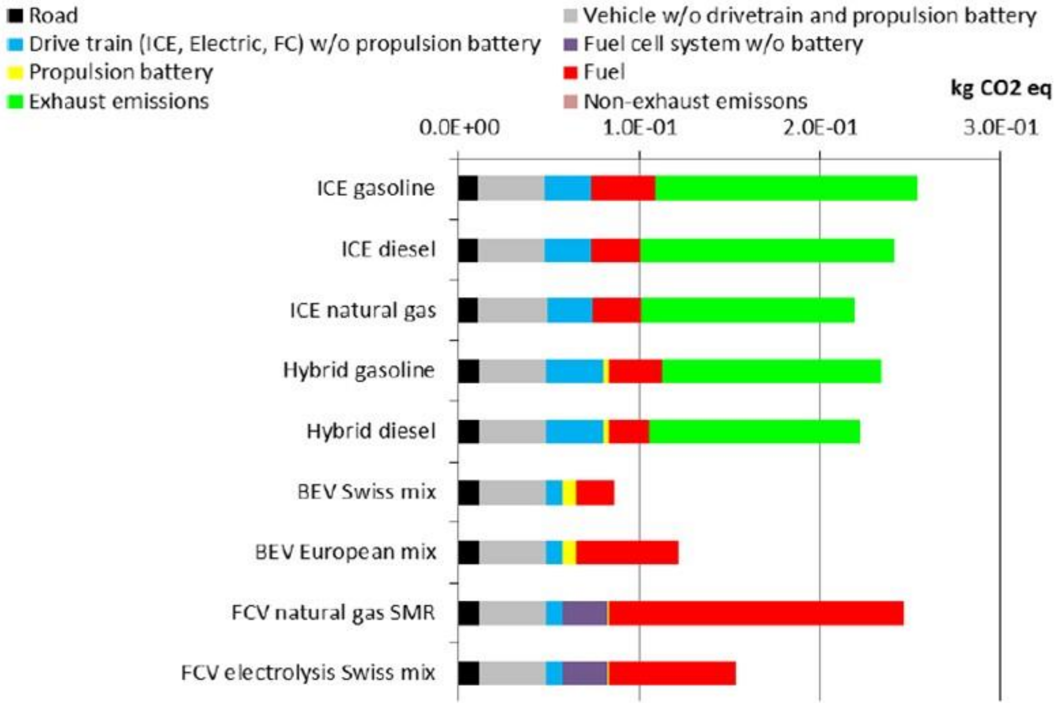
Pollutant	Pollutant (full name)	Acidification	Eutroph-ication	POCP	Particulate matter formation (PMF)
CO	Carbon monoxide	0	0	0.0456	0
NH_3	Ammonia	1.6	0.35	0	0.64
NO_x	Nitrogen oxides	0.5	0.13	1	0.88
$PM_{2.5}$	PM2.5	0	0	0	1
SO_x	Sulphur oxides	1	0	0.0811	0.54
NMVOC	Non-Methane Volatile Organic Compounds	0	0	1	0.012

Source/Notes: Impact factors extracted from SimaPro (2020) for the mid-point categories selected for this project.

2.2.3.2 Differences in impacts between powertrains, fuels and vehicle types

Overall, the findings from the literature review summarised in more detail in Appendix A1 indicate that GWP and other impacts involving airborne pollutants tend to be greater for ICEVs compared to xEVs (i.e. PHEV, REEV, BEV or FCEV) (e.g. see Figure 2.8). On the other hand, xEVs tend to have higher impacts than ICEVs in terms of toxicity and resource use, according to the studies reviewed.

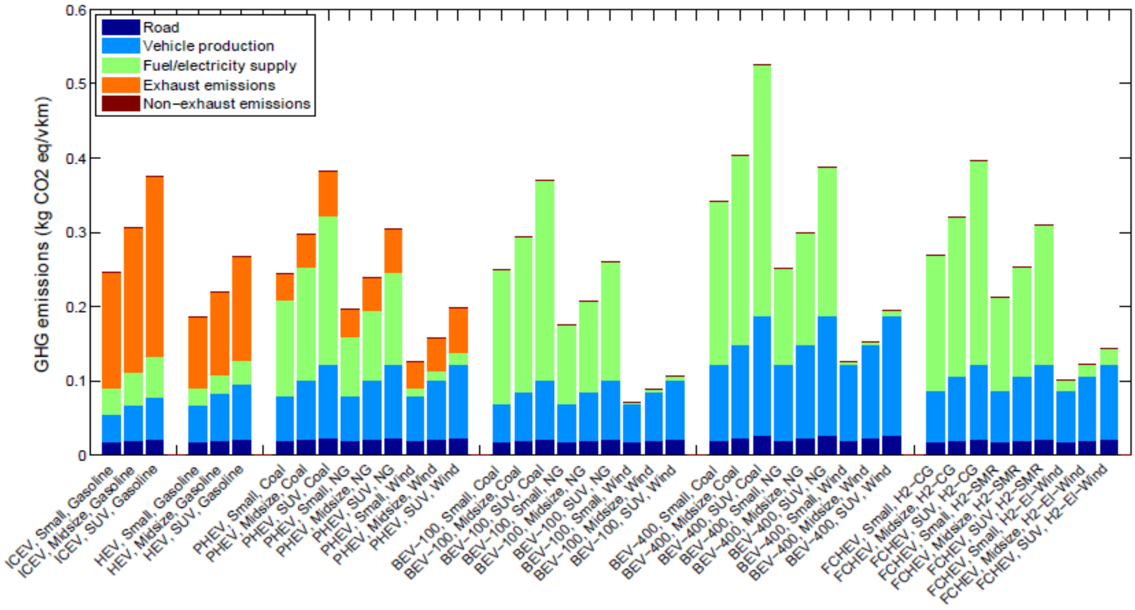
Figure 2.8: Life cycle GHG emissions from passenger cars by powertrain type, Thelma Project



Source: (PSI/EMPA/ETHZ, 2016)

Moreover, regardless of the powertrain type, the magnitude of the impacts (measured in vehicle-kilometres) is found to increase with vehicle weight and lifetime mileage (e.g. see Figure 2.9) and therefore heavier and commercial vehicles are usually responsible for higher absolute burdens. These two factors are key in determining the impacts of HDVs and buses vs those of passenger cars and thus merit special attention in the analysis. It is worth noting that this effect is dependent on the functional unit used (i.e., vehicle-km vs passenger-km for cars or in tonne-km for HDVs). The literature however tends to report results in vehicle-km as discussed in section 2.2.4.1.

Figure 2.9: Life cycle GHG emissions for different vehicle sizes



Source: (Hofer, Simons, & Schenler, 2013)

The type of fuel used, or the source of electricity also determine the magnitude of the vehicle life cycle impacts. The environmental impacts associated with fuel production can significantly differ depending on whether fuel is produced from a biogenic feedstock, fossil feedstock, or electricity, and on how each option is computed in terms of negative impacts. In terms of fuel combustion, whilst the environmental impacts tend to be similar for all liquid fuels, there are key differences in GWP impacts depending on whether the fuel is made of fossil or biogenic carbon. Other impact categories also become more relevant for certain fuel types such as those produced from primary fossil feedstocks and crop/forestry-based feedstocks that are associated to specific land-use change and resource depletion impacts and should thus be considered for the analysis.

Regarding the electricity supply chain in particular, fossil fuel sources exhibit higher overall impacts compared to renewable sources, especially in the case of lignite; natural gas on the other hand shows the lowest burden amongst fossil fuel sources. It follows that the source of electricity is key to the xEVs potential to deliver smaller environmental impacts and is therefore a crucial aspect of the assessment (both in terms of their use phase and manufacturing stage as battery manufacturing is an electricity-intensive process).

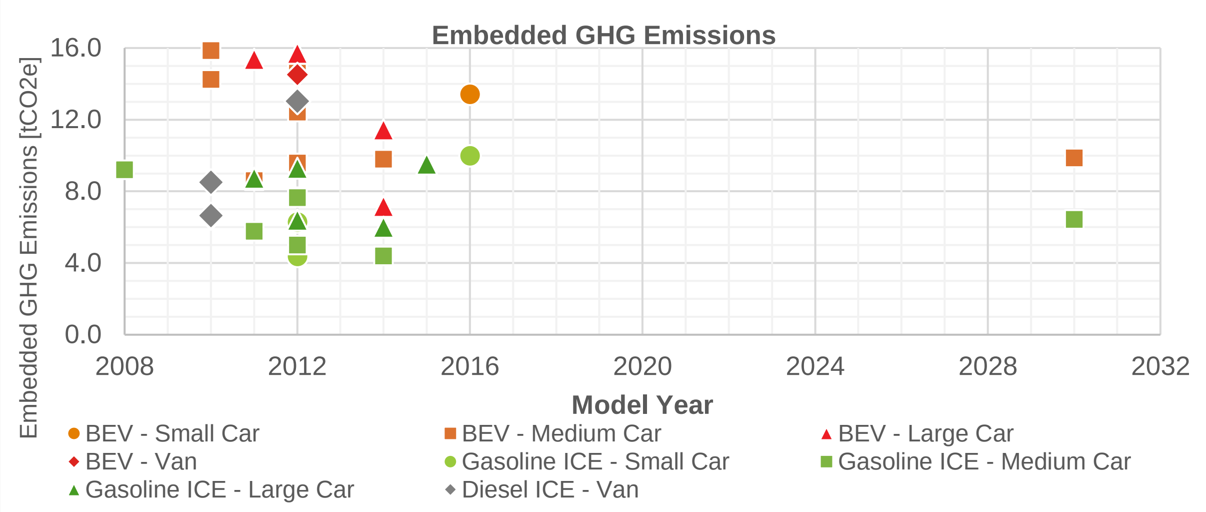
2.2.3.3 Importance of different life cycle stages

The contribution of the different life cycle stages also differs between impact categories, powertrain types and fuel/electricity sources, as the summary of the findings of the literature review provided in Appendix A1 suggests. The vast majority of studies have focused on GHG emissions, however.

Considering first the importance of life cycle stages for the different impact categories, the use phase (TTW) tends to dominate and generate the most GWP impacts in the case of ICEVs, whereas both the vehicle/equipment cycle and the energy supply chain (WWT) contribute the most to GWP impacts from xEVs – which stage dominates xEV impacts depends on the assumptions made (e.g. carbon intensity of electricity/hydrogen) as well as the vehicle size and type. In contrast, other environmental impacts tend to be more strongly linked to vehicle/equipment cycle or the fuel chain and less so to the use phase - even in the case of ICEVs.

Focusing now on the relative importance of life cycle stages for the different powertrain types, it is worth highlighting that the vehicle/equipment cycle of the xEV tends to be responsible for higher absolute (i.e. embedded emission) impacts compared to the equivalent ICEV for all impact categories (e.g. see Figure 2.10), due to the sourcing of materials for vehicle manufacturing – in particular, those required for production of traction batteries. Batteries are a key component of xEVs and thereby warrant a more detailed assessment, today and in light of expected future developments. (This is consequently reflected in the methodological approach developed for this project, discussed in Section 3.5, and also in more detail in Appendix A3).

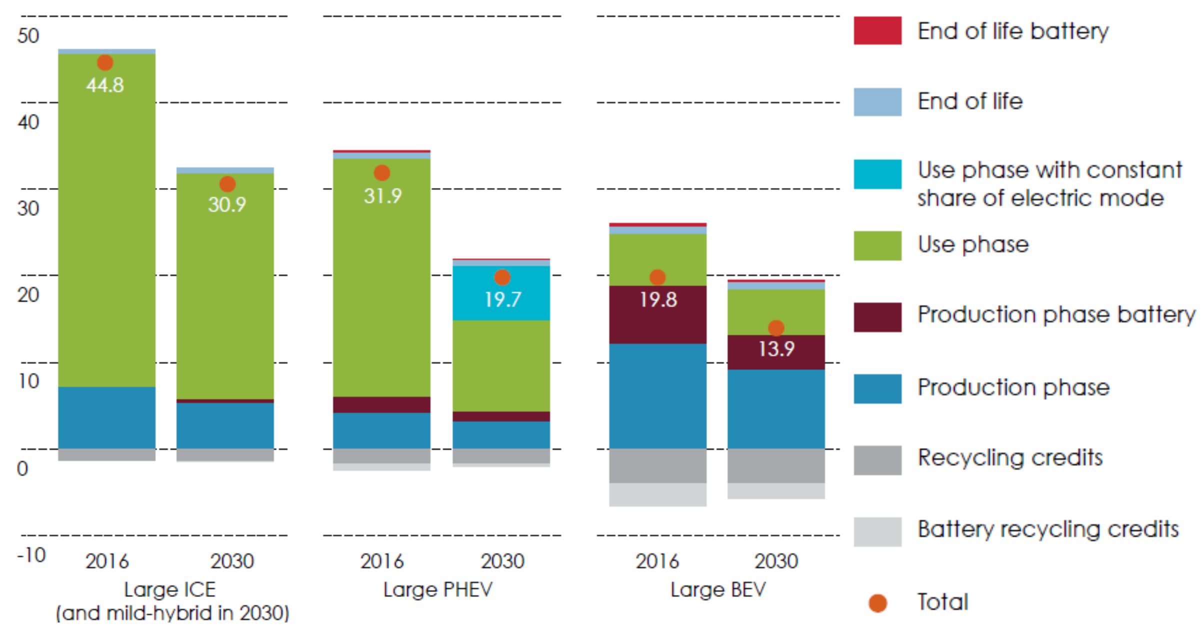
Figure 2.10: Embedded GHG emissions reported by the literature



Notes: Embedded GHG emissions include emissions from vehicle production and end-of-life processes. *Source*: Ricardo, compiled from the literature.

The end of life disposal and recycling stage is not always covered by vehicle LCA studies. However, recycling can compensate in part the negative impacts from vehicle production, particularly from batteries (e.g., see Figure 2.11). This stage should therefore receive more consideration in future studies – especially as there is still significant uncertainty on the net gains due to recycling and how these might develop in the future.

Figure 2.11: Global warming potential: 2016-2030 results compared for the large car sector (tCO_2e)



Source: (ECF, 2017)

When considering fuel combustion (i.e. WTW cycle), key differences exist between fossil fuels and some renewable fuels (e.g. biofuels, biogas, renewable hydrogen): GHG emissions during the use phase are often assumed to be null for the biogenic component of combusted fuels[6], but are very significant in the case of fossil fuels. Fuel combustion is the largest source of emissions across the lifecycle of vehicles powered by fossil fuels. The use of hydrogen does not per se generate GHG emissions during the use phase, but the energy used during the production process may have a fossil origin, thus creating GHG emissions and other impacts upstream.

Differences are also observed amongst different electricity sources. Coal-based electricity produces most GHG emissions in the use phase. On the other hand, electricity from renewable sources have a higher burden in their upstream process due to the mining and processing of materials. Similar contributions are observed for the other environmental impacts.

It follows from the above that the overall impact of the xEV can be lower than that of an equivalent ICEV, if and only if, it can achieve lower impacts from its WTT cycle (i.e. electricity supply) that compensate for the additional burden in the production stage. A good understanding of the burdens of each life cycle stage is therefore central to the analysis.

2.2.3.4 Importance of key parameters and assumptions on the results

The impact estimates reported in the literature and the associated conclusions on the most relevant impacts and life cycle stages are determined by a number of key assumptions (see Appendix A1 for a more detailed discussion). The most relevant assumptions concern the following elements:

- *Carbon intensity of electricity*: determines the significance of the WTW cycle of xEVs and e-fuels, and thus how xEVs perform compared to ICEV. It is linked to *temporal and spatial considerations;*
- *Lifetime mileage*: determines the significance of the WTW cycle and therefore also affects the balance between production and use phases; commercial vehicles which have a higher lifetime mileage therefore have a higher proportion of impacts in their use cycle compared to passenger cars;
- *Driving patterns*: influence the performance of difference powertrain types. Driving in urban roads, which is associated with more stops, gives xEVs an advantage compared to ICEVs (due to regenerative breaking and start and stop capabilities). These assumptions are thus important to determine differences in the benefits of xEVs vs ICEVs – linked to *spatial considerations;*

Many of the assumptions to be made are linked to temporal and/or spatial considerations. Overall vehicle impacts are anticipated to be affected by future changes in technology but also the location of production and/or use of the vehicle. Key factors include:

- Carbon intensity of electricity depends on the energy mix used in the country (often even the sub-national level); Changes in electricity mix are also expected over time (daily, seasonal, compared to study's time horizon);
- Driving patterns depend on the type of roads where vehicles are mainly used (e.g. xEVs provide greater advantage over ICEVs for city driving conditions due to regenerative breaking and start and stop capabilities);
- Improvements in the xEV technology and production in scale are expected over time;
- Fuel/electricity efficiency expected to improve;
- Potential for second-life applications of batteries and V2G applications, recycling;

These are therefore key factors that need to be carefully presented and examined in the analysis.

2.2.4 Summary of the identified methodological options from the literature

A review of the methodological approaches identified in the literature was used in combination with the project team's considerable experience in these areas to inform the development of the methodology to be used in this study. The sections below provide a summary of the key methodological elements taken forward in this study that are supported by the literature. A more detailed description is given in Appendix A1.

[6] The assumptions that there are no CO_2 emissions when biomass is combusted are based on the premise that the CO_2 which is released when biomass is combusted can be discounted as it is of biogenic origin and was originally sequestered from the atmosphere during the growth of the biomass. However a fully assessment would include any changes to carbon stock levels, or soil carbon related to use of the biomass and the impact of any land use change.

2.2.4.1 General methodological options

First, several commonly used guidelines for LCA were identified in the literature review and were used as a reference for methodology development.

- The **ISO 14040/14044** (ISO14040, 2006) (ISO14044, 2006) norms provide the common basis for all LCA studies today in the form of a standard. They include general requirements for all aspects of a products lifecycle, but still leave many methodological aspects to be further defined by the LCA practitioner.
- The **ILCD handbook** (JRC, 2010) was written by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in co-operation with the Environment DG in 2010. It is in line with the ISO standards and consists of several documents: a general guide on lifecycle assessment, a specific guide on lifecycle inventory, a guideline on lifecycle impact assessment methods (including a set of recommended LCIA methods) and a guide on review criteria. With these documents, the ILCD handbook addresses many practical considerations for LCA application beyond the general ISO 14040/14044 requirements.
- The **Product Environmental Footprint (PEF) Guide** (JRC, 2012) provides a harmonised European methodology for Environmental Footprint (EF) studies using a life-cycle approach. This very general guidance document is scheduled to be complimented by more specific Product Category Rules, following the PEFCR guidance (JRC, 2018a). One such Product Category Rule is the **PEFCR for batteries** (RECHARGE, 2018) which provides detailed and comprehensive technical guidance on how to conduct a PEF study for rechargeable batteries. These documents are continuing the guideline discussion on the EU level and are partly also replacing the recommendations from the ILCD handbook, which is not further updated.

Due to the origin, significance and acceptance within the EU context, the ILCD handbook and PEF guide are regarded as a default approach for specific methodological aspects. Other guidelines give provisions for specific aspects or life-cycle phases of the vehicle LCA. Out of those the **eLCAr guidelines** for electro mobility (eLCAr, 2013) and the **FC-Hy Guide** for hydrogen (FC-Hy, 2011) have been analysed. The eLCAr guidelines provide guidance for the LCA of electric vehicles and are based on the ILCD handbook. The idea was to create a common framework concerning methodological choices and assumptions for electric vehicles and enhance the comparability of studies conducted in this field. The FC-Hy Guide has a similar scope. It provides a detailed technical guidance on how to conduct LCAs for fuel cells (FCs) and hydrogen production systems and is also based on the ILCD handbook.

As regards actual LCA studies, when comparing methodological approaches, it is important to take into account the intended application and reasons for carrying out the study. The reviewed literature broadly falls into the following categories (see also the earlier Table 1.2 comparison of product and policy LCA):

- **Company Product LCAs**: These are generally executed or commissioned by large companies (e.g. OEM) as proof of the environmental performance of certain products over the preceding models or other technologies. A critical review is often undertaken not only to ensure compliance with ISO 14044 but also to enhance public credibility. As target audience the general public (costumers, journalists as well as policy makers) can be assumed. Examples for such product LCAs are (Audi, 2011), (Mercedes Benz, 2011), (Mercedes Benz, 2014), (Volkswagen, 2010), (Volkswagen, 2014) and (BMW, 2013).
- **Policy oriented LCAs**: Studies commissioned by political bodies and executed by specialised consulting agencies, institutes and sometimes also universities. These studies are either driven by specific policy decisions (e.g. directives) or intended to inform the general discussion of policy directions. Examples for policy driven LCAs are (ICCT, 2018) and (ECF, 2017). The study at hand clearly falls into this category.
- **Academic LCAs**: These are often executed by Universities or other academic institutions. The level of methodological detail and development is generally higher compared to OEM LCAs. The reviewed academic LCAs also focus on specific subsections of the vehicle life-cycle, e.g. battery production, fuel chains or electricity generation. Motivation can be either industry driven, but often also methodological development is one focus of this type of LCAs. Examples for such academic LCAs are (Peng, 2018), (Lee & Thomas, 2016), (Hawkins et al, 2012) and (Ercan & Tatari, 2015).

Within this reviewed literature, both a vehicle kilometre and a vehicle life have been identified as the most common functional units at the vehicle level. Mobility-related life cycle assessments based on the utility value of the vehicles (i.e. transport of a certain mass or number of people) are scarcely represented in the literature reviewed.

For the impact assessment, finally, a range of endpoint and midpoint indicators have been developed and can be used. Here **endpoint indicators** directly refer to an impact in the field of (i) human health, (ii) natural environment or (iii) resource consumption, and most closely reflect the protected good. **Midpoint indicators** in turn are weighting substances with similar effects along their mechanisms into an impact indicator via characterization factors. It is apparent that most evaluated literature uses midpoint indicators, even though endpoint indicators are described to be better understandable in their potential damage. This is also due to high uncertainties which are associated with the translations from midpoint mechanisms into actual endpoint damages. Some studies also report only individual pollutant emissions, e.g. where they are particularly relevant to regulatory compliance / emissions reporting for particular pollutants. Even though a lot of studies only focus on greenhouse gas emissions, it is important to stress that there is no scientific basis for reducing LCA results to a single overall score or number.

2.2.4.2 Vehicle specification and operation

Broadly speaking, three types of approaches for the characterisation of vehicles and the estimation of operational energy consumption and emissions have been applied in the LCA literature reviewed:

a) ***Simple / high-level characterisation:*** Use of high-level data or assumptions based on typical examples of representative vehicles, or values taken from the literature / public domain.
b) ***Intermediate approaches:*** Based on more detailed, but simplified methodologies / calculations to better account for variations in key parameters between vehicles or powertrains, or more closely define operational usage.
c) ***Complex characterisation:*** Use of more complex methods, such as vehicle tear-downs and complex vehicle simulation approaches.

For the characterisation of the vehicle, analysis suggested a more directly scalable methodological approach based on key vehicle characteristics would be an effective / practicable solution for this study. This is also the approach used in most of the more detailed studies that have aimed to provide a comparative analysis of a range of different types of vehicle / powertrain, e.g. (ANL, 2016), (PSI/EMPA/ETHZ, 2016), (Hawkins et al, 2012). Such an approach can be used to scale the calculation of impacts for a series of generic average vehicle body types in a reasonably robust and consistent way, and allows for flexibility in exploring the potential impacts of sensitivities on key parameters. A summary of the most important elements is provided below, with further information provided in Appendix A1.

Operational energy consumption: There are a spectrum of choices available ranging from taking simple representative values from the literature / public sources (e.g. (Hawkins et al, 2012)), through to complex full vehicle simulation to determine values for specific cycles and different powertrain types on a fully consistent basis (e.g. (PSI/EMPA/ETHZ, 2016), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)). Obviously, those studies that have a narrower focus are often able to adopt more accurate/complex methodologies. Due to the very broad nature of this project, a full simulation approach was not feasible, however accounting for some of the other important elements (such as variation by road type, accounting for mass changes, etc.) were judged to be feasible through simplified methods. For example, it was decided to use approaches based on a combination of existing simulation-based datasets (e.g. for mass / energy consumption relationships, and the relative performance of different powertrains) and other methodologies (e.g. speed-fuel consumption curves/formulae used in emission inventories).

Other exhaust and non-exhaust emissions: For modelling air pollutants, inventory-based methods as well as complex vehicle simulation have been utilised in some studies in order to estimate real-world emissions impacts (Sen, Ercan, & Tatari, 2017), (Lee & Thomas, 2016). Most vehicle LCA by OEMs for environmental product declarations have used emission factors from regulatory testing results, e.g. (Mercedes Benz, 2011). However, these are known to deviate from real-world conditions and were therefore not deemed suitable for this project. It was judged that inventory-based methods (such as COPERT, (Emisia, 2019)) were viable, which would also facilitate accounting for variability in emissions by road type, offering the potential to also explore regional differences.

Vehicle mass and composition: Most of the studies identified adopted information for vehicle mass and material composition based on available information for specific vehicle models (e.g. from literature or other public sources), e.g. (Hawkins et al, 2012). LCA studies developed for OEM environmental product declarations were obviously based on detailed information provided by the manufacturer for the specific models being assessed, e.g. (Mercedes Benz, 2014) and (Renault, 2011). In LCA studies seeking to achieve this aim (e.g. (ANL, 2016), (PSI/EMPA/ETHZ, 2016)), more complex methodologies were usually adopted whereby more transparent and systematic accounting for different components was developed – i.e. typically breaking down the vehicle type into a generic 'glider' and a number of powertrain specific components or systems (groups of components), each with their own material composition and mass definition. As already indicated, this approach was judged to be best-suited and proportionate for this project as it allows presenting a fully consistent comparative analysis of equivalent vehicle / powertrain types as well as more systematic sensitivity analyses.

Battery specification and characteristics: The majority of studies reviewed utilised relatively simple methodologies and assumptions for the sizing and specification of xEV batteries – most commonly based on examples using fixed sizes/specifications from existing vehicles and fixed assumptions on replacements, where this was accounted for, with little accounting for more dynamic interactions with other vehicle parameters. More sophisticated approaches have been used in some studies, notably (ANL, 2016), (PSI/EMPA/ETHZ, 2016), and also in (Ricardo, 2018), (Ricardo Energy & Environment, 2019). In the latter, the methodologies and data from the GREET model (ANL, 2018) have been built upon, and further development on this framework was judged as the optimal approach also for this new project. The characterisation of Li-ion batteries, their manufacturing and recycling in the GREET (and EverBatt) model(s) has been developed and improved over many years by Argonne National Laboratory (ANL) researchers, providing a systematic, detailed and transparent approach.

Lifetime activity: the majority of studies use a simplified approach based on fixed annual mileage profiles and lifetime activity. However, previous analysis for the European Commission by Ricardo (Ricardo-AEA, 2014a), (Ricardo Energy & Environment et al., 2015), and others (TML et al, 2016) has provided a more robust evidence base for actual European lifetime mileage from different vehicle types, and the variation of this with vehicle age has been used previously by Ricardo to provide a more accurate assessment for forward-looking LCA-based policy analysis. Over the life of the vehicle, exhaust emissions are not expected to generally change significantly, however changes in impacts from fuel and electricity production may change substantially.

2.2.4.3 Vehicle manufacturing, maintenance and end-of-life

The reviewed studies vary largely in their goal and scope and accordingly the level of detail in which impacts from vehicle production, maintenance and end-of-life are addressed. Key methodological aspects for each stage are summarised below.

Vehicle production

Three types of studies were identified:

1. **Overview/Meta-studies** focus on the use phase and thus tend to use aggregated data for vehicle production which is taken from other sources and only roughly reflects specific differences between the analysed vehicles (e.g. (ADAC, 2018) which is fully reliant on data from (ifeu, 2016). Such studies are often limited to GHG emissions.
2. **Scientific LCAs on generic vehicle types** often focus on a technology comparison (e.g. (ifeu, 2016), (Hawkins et al, 2012)). Components and materials are typically considered at a higher level of detail and further data is often documented. These data, however, usually reflect an average generic situation and do not claim to exactly resemble a specific vehicle model. Input data is compiled from different sources such as other (component) studies, databases and OEM and proxy data. Such analyses often use a component based modular approach, consider detailed material compositions, and make estimates of energy consumption and auxiliary materials used in the production process.
3. The literature review also comprised numerous **OEM studies** on specific vehicle models (e.g. (Audi, 2011), (Mercedes Benz, 2011), (Mercedes Benz, 2014), (Volkswagen, 2010), (Volkswagen, 2014) and (BMW, 2013)). These mostly use primary data from the OEM and their suppliers but only aggregated results and not the detailed data are published. It can be assumed that further data are available (e.g. from the International Materials Data System (IMDS)) but has to be obtained from the OEM directly.

On the one hand, the use of aggregated values from other studies is a highly practical approach, but is not in line with the goal and scope of this study. On the other hand, a highly differentiated and vehicle specific approach is transparent and is also suitable for temporal and spatial differentiation. However, it is not feasible for the range of vehicle types covered by this study and is also not in line with the goal and scope of the study. Therefore, the methodological approach adopted for this study borrows from the approach of scientific LCAs, focussing on generic vehicles whilst allowing sufficient level of detail to account for all relevant vehicle specification differences. The approach entails using differentiated material compositions, but in a modular/component-based way, and combining these with values for materials from commonly accepted databases.

Vehicle Maintenance

The literature review shows that the number of studies which actually take into account maintenance is small (see Figure 2.5). Those which do give hardly any detail on the methodology and data used for modelling maintenance. Due to the low significance of maintenance generic data from databases are often used. For our study, a simplified approach for dealing with maintenance is also applied and deemed to be sufficient given that maintenance generally does not account for a large share of the overall environmental impacts in the vehicle life cycle.

Vehicle End-of-Life

One area that is commonly not the focus of an LCA study is the vehicle end-of-life phase, however the impacts from this stage can be significant. The main difference in the environmental impacts from this stage in the reviewed literature arise from the choice of the end-of-life modelling method, although some are due to different processes and data sources. A range of options for dealing with end-of-life processes have been identified in the literature reviewed as described in Section 2.2.4.1, and this aspect is discussed in more detail in Section 3.6.1.

For xEV batteries, it is also important to consider their reuse/repurposing for second life. This area is still at a relatively early stage of investigation, and there are relatively few studies available on the potential environmental impacts. Despite the availability of some LCAs of second-use of xEV batteries in the literature (e.g. also (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2015), (Casals, AmanteGarcía, Aguesse, & Iturrondobeitia, 2015)), there are not yet any guidelines or harmonised approaches making comparisons difficult (Ricardo Energy & Environment, 2019) and also according to (JRC, 2018). In particular, different system boundaries are observed in the literature, e.g. assessing the whole life of the xEV battery, or only those stages directly affecting the second-use of the xEV battery.

The review identified a number of alternative approaches for accounting for the impacts of battery second-life, from comparison to a specific reference case, to applying a credit based on assumed equivalent displacement of a new energy storage battery, or using economic allocation based on the value of the used battery at its end-of-life (which are all described in detail in Appendix A2). There is considerable uncertainty on such aspects and stakeholders were consulted specifically on this to decide on the most appropriate methodological approach to take forward in this study.

2.2.4.4 Electricity production chains

This section summarises the key lifecycle analysis approaches for electricity generation described in the literature.

Goal and scope

Depending on the **goal**, but also the investigated technologies or product systems, the **scope** can vary from limiting the analysis to the plant operation and related direct emissions only[7] to a holistic and complex approach including all relevant additional upstream and downstream processes as well as other significant factors as described in the following:

Infrastructure provision, the manufacturing and provision of necessary infrastructure; This includes the infrastructure of the power plant(s) itself, but can also include infrastructure for raw material acquisition, fuel production, roads for transports and infrastructure related to transmission and distribution networks;

Fuel production; comprises the production of fuels such as hard coal or natural gas, but also biomass or nuclear fuels through the means of mining8 (fossils and nuclear fuels) and cultivating (primary

[7] This simplified approach is utilized where the vast majority of impacts is related to the plant operation itself, e.g. lignite burning or natural gas
[8] Both open- and closed pit mining

biomass such as maize). Additionally, fuel production for waste-based power generation usually consists of waste collection and transports only[9].

Plant operation including the actual power generation by means of e.g. burning of coal. Moreover, this also comprises maintenance and other auxiliary processes such as waste disposal.

In addition, ***transmission and distribution*** with accompanying losses influence the results significantly, dependent on the characteristics (most noticeably the distances to be covered and the technologies applied as well as electricity theft) of the investigated system.

Finally, electricity is subject to ***external trade*** as a commodity from one country to another or several others. This has an influence on the environmental impacts (e.g. carbon intensity) when investigating the national consumption mix (the electricity that is consumed in a country) but not on the production mix (the electricity that is produced within a country). For a region like the EU28, these effects cancel each other out, but matter when comparing the consumption mix of a country or on a smaller scale in general.

How are different environmental impacts of electricity generation covered by literature?

Power generation utilizes a broad spectrum of different technologies. This leads to corresponding different impacts, both in terms of quantity and quality. While most studies focus on the GHG intensity (and to a lesser extent on the primary energy demand per unit of energy supplied, e.g. (Kleinertz, Dr. Pellinger, Dr. von Roon, & Hübner, 2018)) of electricity chains, some cover additional categories or comprise/aggregate further categories within a single indicator (e.g. the ecological scarcity method utilized by GaBi). Few studies approach the assessment of impacts in a more holistic way ((Turconi, Boldrin, & Astrup, 2013), (Helms, et al., 2014), (PSI/EMPA/ETHZ, 2016), (Razdan & Garrett, 2015), (Frischknecht, et al., 2014)) but they all differ in terms of applied impact assessment. In most contemporary LCAs, the environmental impacts most commonly covered are:

- *Global Warming Potential,*
- *Acidification Potential,*
- *Eutrophication Potential,*
- *Photochemical Ozone Creation Potential,*
- *Energy Consumption,* and
- *Human Toxicity Potential.*

The different generation technologies differ in respect to their contributing lifecycle phases. For instance, coal powered plants over the course of their technical lifespan will produce most GHG (and other) emissions in the 'use-phase' (referring to the operation of the power plant) of their life cycle, while emissions arising from upstream processes will be negligible in comparison. In contrast, electricity from photovoltaics is virtually emission-free during generation with most emissions related to upstream processes for infrastructure provision like mining and processing of utilised materials as well as installation. Table 2.4 provides an overview over the general relevance of lifecycle stages for the above mentioned impact categories (excluding HTP).

Table 2.4: Qualitative comparison of impacts from different lifecycle stages by electricity generation type for different environmental impact categories

Type	Lifecycle stage	GWP	AP	EUT	POCP	ADP
Coal	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	-	-	-	-	-
	Plant operation	++	+	++	+	++
Fuel Oil	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	-	-	-	-	-
	Plant operation	++	++	+	++	++

[9] Other treatment options and related emissions are attributed to the waste-generating process / product system that preceded the treatment.

Type	Lifecycle stage	GWP	AP	EUT	POCP	ADP
Natural Gas	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	-	-	-	-	-
	Plant operation	+	Ø	-	Ø	+
Biomass[1]	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	+	+	+	-	-
	Plant operation	Ø	Ø	Ø	Ø	-
Biogas[2]	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	+	-	-	-	-
	Plant operation	+	Ø	-	Ø	-
PV	Infrastructure/upstream	-	-	-	-	-
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--
Wind	Infrastructure/upstream	-	-	-	-	-
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--
Hydro	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--

Key: ++ = very high impact, + = high impact; - = low impact; -- = very low impact; Ø = intermediate impact;

Notes: Excluding waste biomass. Exact values dependent on the type of biomass, e.g. wooden biomass carries other burdens than crops.

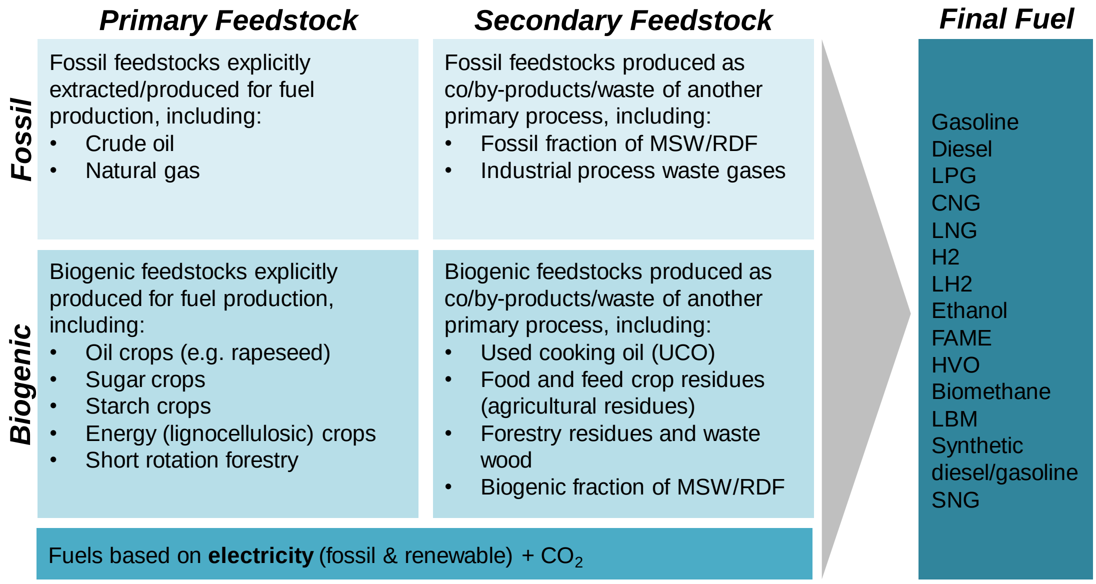
A more detailed analysis of the investigated literature concerning the coverage of electricity production in the literature, can be found in Appendix A1.

2.2.4.5 Fuel production chains

A large number of publications exist, which attempt to evaluate environmental impacts of fuel chains, but a significant share of these are focused on greenhouse gas emissions. A large share of the publications reviewed aimed at comparing fossil fuels to conventional biofuels and, to a lesser extent, advanced biofuels. The number of publications looking at more recent alternative fuels (e.g. e-fuels and synthetic fuels) is more limited. Literature is more scarce for the most recent alternative fuels such as synthetic fuels or e-fuels, which impacted the robustness of some of the data used in modelling of these fuel chains (See also Section 4.45.3).

Five fuel categories were considered in this study, as illustrated in Figure 2.12. For both fossil and biogenic categories, primary fuels (i.e. those requiring the dedicated extraction or cultivation of raw material such as crude oil, natural gas, crops or wood) are distinct from secondary fuels (i.e. those produced from residues and wastes generated by other supply chains). The fifth category includes all fuels produced from electricity (e-fuels), including hydrogen and other derived synthetic fuels.

Figure 2.12: Classification of fuels by primary and secondary fossil and biogenic feedstocks



The following section describes key environmental hotspots for the different fuel categories, as found in the literature review and which were integrated in the methodological choices in this study.

For ***primary fossil fuels*** (diesel, gasoline, CNG, LNG):

- While powertrains can be compared on equal grounds in a Well-to-Wheel scope (incl. energy source), fuels cannot all be compared, due to the emissions occurring during combustion. Combustion emissions are a very important differentiator between fossil fuels, biogenic fuels and e-fuels. They are however included in the Tank-to-Wheel stage of the vehicle life-cycle, and therefore missing from the Well-to-Tank stage. This is why system boundaries needed to be expanded from Well-to-Tank to incorporate greenhouse gas emissions from combustion for primary fossil fuels.
- Co-products could be addressed in various ways, but an economic allocation was recommended in several publications as the appropriate approach. Eventually, it was decided to use the ifeu refinery model, which implements an energy allocation.
- Methane leakage, venting and flaring must be included, as they represent potentially significant contributions to GHG emissions.

For ***secondary fossil fuels*** (e.g. ethanol from waste industrial gases):

- As with fossil fuels, GHG emissions from combustion were added to the rest of the Well-to-Tank emissions.
- Feedstocks considered as waste (e.g. manure) generally enter LCA systems burden free and in current EU policy, residues, including tree tops and branches (Forestry residues), straw, husks, cobs and nut shells (i.e. agricultural residues), and residues from processing (e.g. saw dust), are not be attributed any GHG emissions before the first collection point (RED II – Annex V, Par. C.18). It has been identified in literature that diverting secondary feedstocks from existing uses to fuel production could have unintended impacts (E4tech, 2018), which could be taken into account using a consequential LCA approach. In such approach, the consequence of avoided counterfactual uses (e.g. power generation through waste incineration) would be assessed, both as avoided impacts but also as additional impacts (e.g. by generating an equivalent amount of power from the grid).
- Waste fossil feedstocks originate from either industrial processes or dedicated waste collection and the associated environmental burdens have to be accounted for carefully in life cycle assessment to ensure that any potential emissions savings are not double-counted at any point in-between possible system boundaries. This applies in particular to industrial waste gases or separated and captured CO_2.

- CO_2 as a feedstock does not contain any energy, and to produce a transport fuel all catalytic synthesis processes require hydrogen to react with the CO_2 and in microbial synthesis the microbes require H_2 to process the CO_2 into methane. This means that a clear hot spot is the environmental impact associated with the production of hydrogen.

For ***primary biogenic fuels***:

- Agricultural inputs such as pesticides and fertilisers can cause significant, albeit difficult to generalise environmental impacts. Impacts are heavily dependent on local circumstances (e.g. soil types, precipitation, geology, other agricultural practices) and vary by crop. Various datasets were identified, which contain comprehensive inventories for agricultural inputs applied to the crops identified in the scope (e.g. Ecoinvent).
- Direct land-use change (LUC) emissions are well understood and quantifiable, e.g. through IPCC's LUC emission factors. However, indirect land-use change caused by feedstock diversion is more complicated to model and generally not included in the scope of biofuel LCAs or policies. Indirect land use change (ILUC) includes GHG losses due to land conversion, as well as soil organic carbon (SOC) losses during cultivation. Several sources of ILUC data were identified, including GLOBIOM and GTAP models, which both have a large number of publications and reports published over the past few years.
- Biogenic fuels have specific impacts (LCA midpoints), which might be of lesser importance for other fuel chains, e.g. acidification or eutrophication; these impacts are primarily due to agricultural practices.
- Modelling the carbon cycle for crops and forests is complex, especially when integrating the temporality of emissions, which has led to intense debate over the past few years regarding carbon debt and carbon parity periods, esp. for forest biomass for electricity. Most biofuel studies and policies assume, however, that CO_2 combustion emissions are equivalent to CO_2 uptakes. A similar approach was used in this study.

For ***secondary biogenic fuels***:

- As with secondary fossil fuels, literature suggests that counterfactual uses of secondary biomass should be assessed and integrated in LCAs. This is the approach adopted for the fuel chain modelling in this study.
- As with primary biogenic fuels, assuming the CO_2 uptake and release is net zero could be an inaccurate simplification in some cases. This is however the approach taken in a large number of publications and policies.

For ***e-fuels (including hydrogen)***:

- Several approaches are documented in literature for multi-functionality, which vary according to the hydrogen production process. For instance, it is suggested to address co-products in SMR via system expansion, while literature suggests using an economic allocation for co-products in electrolysis-based hydrogen and synthetic fuels.
- As with other fuels, specific midpoints (impacts) are of higher relevant for e-fuels, e.g. acidification, eutrophication or photochemical ozone creation.

2.3 Summary of the stakeholder consultation

Throughout the course of this study, a range of stakeholder consultation activities were organised to support the development and application of the methodology, and the data collection activities. These are outlined in Table 2.5 and described in more detail in the following sections.

Table 2.5: Stakeholder consultation carried out in this study

Consultation activity	Description	Study element contributed to
Delphi survey	Two-round survey to confirm methodological aspects that are particularly complex or involve significant uncertainty.	Development of LCA methodology

Consultation activity	Description	Study element contributed to
Workshops	An LCA expert workshop to present initial methodology proposals, the literature review findings, and first-round survey results, and gather feedback from stakeholders to validate key methodological issues. A final meeting to present and discuss draft findings from the work and recommendations.	Development of LCA methodology Application of the LCA methodology General conclusions
Data validation exercises and ad-hoc data requests	Two validation exercises, and ad-hoc data requests were used to gather/validate data and key assumptions to be used in the application of the methodology.	Application of the LCA methodology

2.3.1 Delphi survey

The objective of the Delphi Survey was to obtain inputs and gain validation from a group of experts on the LCA methodology. The online survey, which was carried out in two rounds, focused on those methodological aspects that are particularly complex or involve significant uncertainty.

The first round was sent to a sub-group of stakeholders, selected on the basis of their expertise in LCAs or in related areas of interest to the study in December. It asked stakeholders to provide their views and/or agreement with the initial proposals for the LCA methodology, which were summarised in an accompanying reference document. The survey was divided into five sections: one on the overall methodological approach and one for each of the specific topic areas under consideration for this study (vehicle specifications and operational emissions; vehicle production, maintenance and disposal; liquid and gaseous fuel lifecycles; electricity lifecycle). Whilst all respondents were requested to answer the questions on the section on the overall methodological approach, they could select which of the following topic-specific sections they would provide answers to. Overall, 35 stakeholders responded, and an overview of their responses is provided in Appendix A2, together with a response from the project team for each of the questions, which summarises the methodological elements taken forward, or provides further clarifications or justification in response to the comments and questions raised by stakeholders.

In light of the feedback received from the first round of the survey and the expert workshop (see below), it was decided to adapt the approach to the second round of the survey and deviate from the classic Delphi process. For methodological elements which had achieved a sufficient level of support in the first-round survey, a summary of the methodological choice which had been supported was provided, with an opportunity for respondents to provide further comments, if they wished. This allowed the main focus of the second round of the survey to be on methodological aspects which did not gather sufficient support or for which alternative choices were possible. For these cases, a specific way forward was proposed, and new or more refined questions were included in the second-round questionnaire.

The second round of the Delphi Survey was in late March 2019. Given the new approach, participation in the first round of the survey was not a pre-requisite for taking part in the second round. Overall, 42 stakeholders responded to the survey. After completion, an anonymised summary of the responses received was prepared and circulated to all participants and the wider stakeholder group. This summary is provided in Appendix A2.

2.3.2 Workshops/meetings

Two workshops/meetings were held with stakeholders:

- An expert workshop to validate the proposed methodology in Brussels in February 2019.
- A final meeting to present the results to a wider set of stakeholders in Brussels in January 2020.

The first expert workshop was attended by 37 stakeholders, including experts in LCA from a range of areas and backgrounds. The majority of these had also responded to the first round of the Delphi Survey. The objectives of the workshop were to:

- Present draft findings from the study to date, including the initial methodology proposals, the literature review findings, and first-round survey results.
- Gather feedback from stakeholders in order to validate key methodological issues.
- Help build support on methodological aspects that are particularly complex or involve significant uncertainty.

The day included sessions for each of the topic areas, when the project team presented their findings and the proposed methodological approaches. These were followed by break-out sessions where participants were asked to discuss a number of key questions. Following the workshop, the feedback provided during the break-out discussions was summarised and included in the copy of the presentations shared with stakeholders.

The second event was attended by 69 stakeholders from a broader range of organisations. The main aim of the event was for the team to present the study and its key results, and it therefore included sessions on the objectives of the work and the methodology developed, the draft findings of the work focusing on the different areas of application including the vehicle, electricity and fuel chains as well as key sensitivities on the results and conclusions and recommendations of the work. Stakeholders were invited to provide comments and questions at the end of each session and a final Q&A session was included at the end of the day when questions submitted by participants throughout the day were answered. All questions were borne in mind during the drafting of this report, and answers can therefore be found in the relevant sections of the report.

Further information on the workshops/meetings and feedback received from/after these is also provided in Appendix A2 of this report.

2.3.3 Data validation exercises and ad-hoc data requests

During the application phase of the study, two data validation exercises were organised to obtain expert input on key data and assumptions on vehicle parameters. As this data is often confidential, rather than simply directly requesting data from stakeholders, available data was first collated, and then the validity of the datasets and underlying assumptions were tested with stakeholders.

This exercise was limited to a set of key assumptions and data where there is also greater uncertainty (e.g. relating to new powertrain components, mileage or electric range assumptions, etc). The first data validation exercise focused on the datasets on the material composition of the baseline vehicles. The second exercise asked stakeholders to provide feedback on a number of key assumptions and scaling factors on the alternative powertrains, including:

- xEV and AFV storage and range assumptions
- Engine and motor scaling assumptions
- Fuel cell system assumptions
- Battery system assumptions
- Efficiency and activity assumptions

For both exercises, stakeholders were asked to review the information and suggest any improvements or amendments to the datasets. In total, we received nine responses to the first exercise and eight responses to the second exercise. The data and assumptions were subsequently revised in line with the feedback provided or further clarifications were sought from these respondents where needed.

In addition, specific data requests were made to fill a number of data gaps or confirm certain assumptions for the application of the methodology.

3 LCA methodology

This chapter provides a summary of the methodology developed during the course of the project, with more extensive detail provided in Appendix A3 of this report.

The development of the methodology and its application is intended to inform the policy-makers about the potential future development of climate change, energy, air quality, and transport related impacts resulting from policies for the mid- to long-term timeframe (2020 to 2050). As such, key criteria used to define the appropriate methodology in this study were:

- **Compliance with goal and scope**: Suitability to inform decision-making.
- **Relevance of overall expected impact**: Elements expected to exert high environmental impacts require more detailed consideration and finer analysis, e.g. as part of sensitivity analysis.
- **Appropriateness for the object of investigation**: The objects of investigation are road transport vehicles and the methodology should cover the key impacts currently associated with road transport and its upstream processes.
- **Transparency**: Transparency is important especially in the context of democratic, science-informed policy making open to public scrutiny. This concerns transparency of underlying data as well as methodological transparency.
- **Suitability for spatial and temporal differentiation**: Spatial and temporal differentiation is a clear goal of the study and of importance to inform policy making on an EU level. The methodology should thus allow for scenario building by e.g. varying key parameters. Furthermore, it should be assessed for which aspects a spatial differentiation is meaningful and feasible.
- **Suitability for application at the individual vehicle level:** a harmonised LCA applicable for reporting emission profiles of individual products in a legislative context is not the intended outcome of this study, and any necessary adaptions and limitations of the methodology in that respect are highlighted.
- **Balancing available resources for application:** the scope of the assessment is very broad – i.e. covering a range of different vehicle types, fuels and electricity chains, and looking out to 2050. The developed methodology therefore also needs to reflect the available resources for this 18-month study, e.g. full vehicle simulation is not feasible, and attention is necessarily focussed on the most important options and impact types.

3.1 Overall LCA methodological approach

The basic framework for developing the LCA methodology under this study has been derived through the following process:

- Extensive literature review covering 347 sources
- Two rounds of stakeholder Delphi survey (see Section 2.3.1 and Appendix A2)
- Stakeholder workshop in Brussels on February 25th, 2019 and subsequent feedback
- Final stakeholder meeting in Brussels on January 16th, 2020 and subsequent feedback.

The overall methodological choices based on this process are documented in the following sections. These choices are guided by the goal and scope on the one hand and practical feasibility for application on the other hand. Furthermore, the relevance of the overall impact, the appropriateness for the object of investigation and the suitability for a spatial and temporal differentiation have been taken into account. Table 3.1 gives a summary of key aspects of the methodological framework and indicates the section in this report which provides further details. Further details on the approaches and a justification of the choices made in this study are given in the Appendix A3.

Table 3.1: Basic methodological framework for the LCA study

Issue	Approach used in this LCA study	Report Section
Goal	Enhance the understanding of life-cycle impacts of transport vehicles on a quantitative basis and create a basis for monitoring/comparison/benchmarking of various vehicle/fuel combinations.	Section 3.1.1
Product system(s)	Seven different types of road vehicles (light and heavy duty) with sixteen different powertrain options are analysed (in total 65 combinations). Furthermore different fuel and electricity chains potentially applicable to the analysed vehicles are included in the analysis.	Section 3.1.1
Functional unit and reference flows	Technical comparisons of vehicles similar in size and utility, which are defined by the vehicle type, size class (e.g. GVW) and potentially segment (for passenger cars). Vehicle kilometre and vehicle-life are the main reference flow for life-cycle results, additional units are used for interim results.	Section 3.1.2
System boundaries	Whole life cycle of the vehicles themselves, from manufacturing and fuel/ electricity production to the use phase (including maintenance) and the end-of-life. Additionally infrastructure for energy production (electricity and fuels) is included.	Section 3.1.2
LCA approaches	Overall a consistent attributional approach is applied. For fuel chains elements of consequential LCA were introduced to evaluate the impact of diverting secondary feedstocks from its counterfactual use to fuel production.	Section 3.1.4
Vehicle end-of-life	Application of the PEF 'Circular Footprint Formula' (CFF), which represents a more sophisticated hybrid approach combining aspects of cut-off and avoided burden approach, as well as accounting for material quality and allocation between the material supplier and recycler. In practice a cut-off approach is effectively resulting for some materials where there is an even balance between use of secondary material and recycling rate, nor quality considerations. An additional credit is given for selected materials where the recycling rate exceeds the content of secondary material.	Section 3.1.4
Temporal development	The time horizon for the study is today (2020) as well as 2030, 2040 and 2050 (with two high-level scenarios based on EC modelling analysis used as a basis for this exploration: Baseline and Tech1.5). The main temporal variations are changes in the European electricity mixes, changes in vehicle energy demand, changes in the fossil and renewable fuel supply, changes in vehicle manufacturing (e.g. different materialisation, vehicle weight, production processes and higher recycling rates) and changes in the impacts from material production (decarbonisation of the used energy).	Within Sections 3.2 - 3.6
Impact categories	Commonly established midpoint indicators including greenhouse gas emissions, acidification, eutrophication, summer smog, ozone depletion, ionising radiation, particulate matter formation, human toxicity, eco-toxicity, resource depletion, land use and water scarcity.	Section 3.1.5
LCI background data	For the background system ecoinvent is used as a transparent and established data base. Where the quality of the original Ecoinvent datasets was not sufficient, data from other sources is used.	Section 3.2
Foreground data: electricity production	Electricity module based on existing ifeu model including upstream fuel chains, power plant processes, distribution of electricity and production of capital goods for the major generation types (hard coal, brown coal (lignite), fuel oil, natural and derived gases, biomass (solid and biogas), nuclear, solar, hydro and wind power). EU electricity conversion	Section 3.3

Issue	Approach used in this LCA study	Report Section
	efficiency, generation mix, losses and imports/exports from EC energy modelling outputs. Non-EU electricity generation mix based on IEA projections for key global regions.	
Foreground data: fuel production	Due to the large number and diversity of feedstocks and fuels covered, a combination of datasets from different sources was required. No single publicly available dataset includes full lifecycle inputs and outputs for the 60 fuel chains modelled in this study. Most conventional fossil and biofuels are well documented in LCA datasets and other mainstream studies. Land-use change, SOC emissions and N_2O emissions were included for primary biogenic fuels, whereas counterfactuals for secondary biogenic fuels were assessed. For less commercially mature fuels, e.g. synthetic fuels, secondary fossil fuels or e-fuels, data was not as readily available. In some instances, single peer-reviewed publications for a lifecycle stage were combined with other datasets for lifecycle stages. All assumptions used to combine datasets from different sources have been documented in the model.	Section 3.4
Foreground data: vehicle specification	High-quality sources used to characterise vehicles and powertrains. Datasets based on market average input data used to define reference vehicle powertrains and average vehicle lifetime/activity, together with recent studies for the EC. Modular component-based approach use for powertrain specification using datasets based on existing high-quality sources, with key assumptions validated with Ricardo experts and external expert stakeholders. Detailed assumptions used to define battery sizing /performance and the variation in operational energy consumption of vehicles. Operational pollutant emissions based on inventory-based methodologies. Sensitivities defined for all the most influential parameters.	Section 3.5
Foreground data: vehicle cycle	Vehicle manufacturing based on material use in vehicles/components, generic manufacturing loss factors, and assumptions on recycled content. Detailed specific characterisation of battery manufacturing and end-of-life based predominantly on data/methodologies applied in the GREET life-cycle model. Maintenance based on replacement components/consumables. Spatial and temporal considerations applied to account for regional shares of manufacturing of vehicles and batteries (separately). End-of-life treatment impacts/credits as indicated above.	Section 3.6

3.1.1 Goal and scope

To inform decision making, it is important to develop a better understanding of the impacts of road vehicles over their entire lifecycle and across a range of potential environmental impact categories. Life cycle assessment (LCA) enables the comparison of different vehicle technologies, including fuel options, on a like-for-like basis. An LCA can help identify key impacts and hotspots throughout the different life cycle stages, in order to better understand the range of opportunities to reduce them, as well as mitigate any potential burden shifting.

The aim of this study therefore is to look into the environmental impact of a representative sample of road vehicles in a holistic manner, using a life-cycle assessment (LCA) approach covering vehicle production, use/operation of vehicles including fuel and electricity production, as well as vehicle end-of-Life (see Figure 3.1). It is meant to enhance the Commission's understanding of potential impacts in the mid- to long-term time frame (until 2050), and of suitable methodologies to assess them.

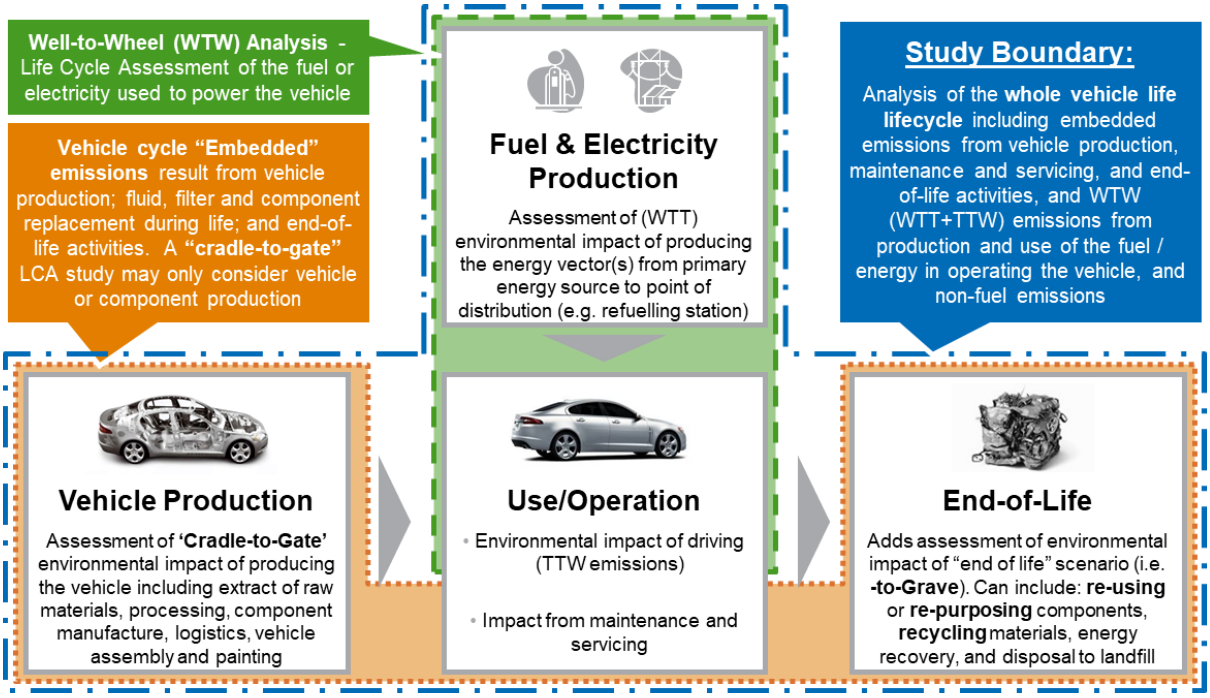
The analysed product systems cover light- and heavy-duty vehicles; namely, two passenger cars (M1 vehicle – Lower Medium, Large SUV segments), a light commercial vehicle (LCV)/Van (N1 Class III vehicle), a rigid lorry (N2 vehicle, 12 t GVW), an articulated lorry (N3 vehicle, 40 t GVW), an urban bus

(M3 vehicle, 12 m SD) and a coach (M3 vehicle, 24 t GVW SD)[10]. Different product systems on the vehicle side are defined by a vehicle type and a meaningful powertrain combination (see Table 3.2).

General vehicle body types (i.e. car, van, rigid lorry, articulated lorry, urban bus, coach) have been defined to apply to all major powertrain types, with variations between these based on adjustment of individual powertrain components based on the specific powertrain.

A more detailed overview of the goal and product systems is provided in Appendices A3.1 and A3.4.

Figure 3.1: Schematic scope of the assessment (system boundaries)



Note: Infrastructure for energy production (electricity and fuels) is also included. Electricity storage is excluded.

Table 3.2: Summary of vehicle types and segments covered in the analysis

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV*	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck (SD)	Typical Single Deck, 24 t GVW
Gasoline ICEV	Y	Y				
Diesel ICEV	Y	Y	Y	Y	Y	Y
CNG ICEV	Y	Y	Y***		Y***	Y***
LPG ICEV	Y	Y				
LNG ICEV			Y***	Y***	Y	Y***
Gasoline HEV	Y	Y				
Diesel HEV	Y	Y	Y	Y	Y	Y
Gasoline PHEV	Y	Y				
Diesel PHEV	Y	Y	Y	Y	Y	Y
BEV	Y	Y	Y	Y	Y	Y

[10] Further information on European vehicle classifications are available here: https://www.eafo.eu/knowledge-center/european-vehicle-categories

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV*	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck (SD)	Typical Single Deck, 24 t GVW
FCEV	Y	Y	Y	Y	Y	Y
FC-REEV			Y	Y		Y
Diesel HEV-ERS				Y		
BEV-ERS				Y	Y**	

Notes: * Based on EU registrations-weighted averages for: Lower Medium = defined as segment C vehicles (e.g. VW Golf) and medium SUVs (e.g. Nissan Qashqai); Large SUV = Large SUVs / Crossovers (e.g. BMW X5, Land Rover Range Rover, Volkswagen Touareg, Volvo XC90, etc.). **Urban bus using regular ultra-rapid charging via a pantograph connection at stops along its route, enabling a significantly smaller on-board battery. Not a trolleybus. *** Modelled with two variants each: -CNG and -CNG lean-burn; -LNG and -LNG/Diesel HPDI.

ICEV	:	Conventional (and mild hybrid) Internal Combustion Engine Vehicle
HEV	:	Full Hybrid Electric Vehicle
PHEV	:	Plug-in Hybrid Electric Vehicle
BEV	:	Battery Electric Vehicle
FCEV	:	Hydrogen Fuel Cell Electric Vehicle
FC-REEV	:	Hydrogen Fuel Cell Range Extended Electric Vehicle
HEV/BEV-ERS	:	Hybrid / Battery Electric Vehicle that can also operate on a catenary Electric Road System

3.1.2 Functional units and reference flows

The functional unit is defined along the lines of vehicle size and utility. The study therefore carries out a technical comparison of vehicle/powertrain variants which are similar in size and utility. Size and utility of the vehicle are largely defined by the vehicle type and size class (e.g. GVW) described above. In such a technical comparison, the same average use characteristics of different vehicle types and segments in terms of lifetime mileage and drive profile is considered for all powertrain options.

A vehicle kilometre (vkm) is used as the main reference flow for the full vehicle life-cycle in this technical comparison, as presented in this report (see Section 5). Results for the vehicle-life will be calculable from the data in the Vehicle LCA Results Viewer provided alongside this report: these results can easily be derived from the vehicle kilometre result using the lifetime mileage (derived from recent analysis and modelling for the Commission, see (Ricardo-AEA, 2014a) and (Ricardo Energy & Environment et al., 2015)). Also tonne-km (tkm) for goods transport are calculated using appropriate load factors, and are the default reference flow unit used in the results section of report for rigid and articulated lorries.

Table 3.3Provies a summary of the default reference flows provided in this report. A more detailed overview of the functional units and reference flows selected for this study is provided in Appendix A3.5.

Table 3.3: Summary of the default vehicle LCA reference flows

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Default reference flow	Vehicle-km (vkm)	Vehicle-km (vkm)	Tonne-km (tkm)	Tonne-km (tkm)	Vehicle-km (vkm)	Vehicle-km (vkm)

3.1.3 System boundary

The analysed scope includes all relevant processes directly related to the use of transport vehicles. The methodological boundary thus encompasses the whole life cycle of the vehicles themselves, from manufacturing and fuel and electricity production to the use phase and the end-of-life (end-of-life treatment criteria are discussed in later Section 3.6.1).

Since all vehicles analysed would have comparable impacts for road infrastructure (e.g. streets or parking spaces), these elements are omitted from the analyses. Charging and refuelling infrastructure could potentially be relevant in a comparative assessment of alternative powertrains (e.g. residential/public, slow/fast/rapid charging, hydrogen pumps, road electrification). Since they were not included in the technical specification for the scope of this project and as data availability is limited, they are omitted for the time being. Charging and refuelling infrastructure should be reconsidered for specific technologies (especially electric road systems) if further studies are carried out in the future.

Production infrastructure for vehicle manufacturing plants is also omitted due to their expected low significance. In the energy sector, however, infrastructure is relevant when looking at certain renewable energies (e.g. solar power) for which most impacts occur from the infrastructure rather than generation stage. Infrastructure for energy production (electricity and fuels) is therefore included.

The time horizon for the study is today (2020) as well as 2030, 2040 and 2050 (using scenarios based on previous analysis by the Commission). The study focus is on establishing current environmental impacts as a solid baseline for the scenarios, in which technological developments as well as the impacts from environmental policies (e.g. CO_2 vehicle fleet targets, Fuel Quality Directive and Renewable Energy Directive) are included. An overview of the core system boundaries is provided in Figure 3.1 above.

A more detailed overview of the system boundary is provided in Appendix A3.5.

3.1.4 General LCA methodological approaches

In respect to the general LCA approach, the ILCD handbook was followed due to its origin, significance and acceptance in the EU context. Accordingly, first of all an overall consistent attributional approach was used. Since the scope of the study also comprises the analysis of scenarios for future impacts until 2050, additional consequential analyses have been undertaken (mainly used in this study to provide alternative results as sensitivity). This hybrid LCA approach, further refined also in the application stage of the LCA, is not only in line with the ILCD handbook, but was also largely confirmed as appropriate by the stakeholder consultation.

For fuel chains, elements of consequential LCA were used to evaluate the impact of diverting secondary feedstocks from its counterfactual use to fuel production (see chapter 3.4). For electricity generation, the generation mix/composition (and also the generation efficiencies and losses) are based on EU energy system modelling scenarios (see later Section 4.7.1), which incorporate already the demands from electric vehicles (as well as other sectors) in the additional capacity added as a consequence of changes in demand. Further consequential impacts could potentially occur in the material chains. These, however, are not usually considered in the respective background data. Here only certain elements of potentially consequential nature (new battery cell chemistries, higher process efficiencies through economies of scale, electricity split and decarbonisation of materials) are considered in the scenarios of battery and fuel cell production.

For the vehicle end-of-life process a hybrid approach was initially proposed to account for the very different situations in respect to recycled content and recycling rate. This approach is consistent with the PEF (Product Environmental Footprint) 'Circular Footprint Formula' (PEF CFF) also included in the battery PEFCR (Product Environmental Footprint Category Rules) (RECHARGE, 2018), though it is a more simplified form. In the PEF CFF an allocation factor between the first and the second user of a certain material is introduced, as well as factors to account for a potential difference in quality of virgin and recycled materials. This formula basically covers the cut-off and avoided burden approach as marginal cases, and was the choice favoured by most stakeholders during the consultation for this project, though there was no consensus.

Approaches to End-of-life (EoL) modelling have been broadly discussed within the LCA community in recent years and while there is still no overall consensus on the single best approach, there is a growing trend towards using the PEF CFF (JRC, 2018a)[11] methodological approach in the EU. From a legislative context, the question surrounding treatment of EoL is whether the focus is more on promoting recycling, or use of secondary materials. The PEF CFF has been developed, in part, to account for the variation of this focus for different materials, as well as to account for other factors, such as differences in the quality of input and output materials. We therefore used the PEF CFF as the basis for the EoL accounting for both vehicles and batteries.

[11] Further information is available here: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

This largely ensures a robust and conservative approach which suits the policymaker's viewpoint, since environmental burdens are accounted for when they actually occur. Additionally, the approach does justice to materials with a potentially significant difference between recycled content and recycling/recovery rates (e.g. steel and aluminium, but also battery cell materials), as well as accounting for quality aspects and allocation between the user and producer of secondary materials.

More details on the multifunctionality and EoL approaches is provided in Appendices A3.7 and A3.8.

3.1.5 Impact categories

3.1.5.1 Selected impact categories

To reduce uncertainty, the assessment relies on commonly established midpoint indicators instead of more aggregated endpoints. Additionally, individual inventory results are given based upon their regulatory significance for transport (see chapter 3.1.5.2). This includes CO_2, CH_4, N_2O, NH_3, NOx SOx, PM_{10}, $PM_{2.5}$, and NMVOC. Energy consumption is calculated separately for non-renewable and renewable energy. Since the recommendations on appropriate impact categories from the ILCD handbook already date back to 2010, the latest PEF supporting information (JRC, 2018) has been used as a guideline.

All categories listed in this document were considered for the assessment. However, in some categories (especially for eutrophication, acidification, particulate matter and land use) diverging LCIA categories were chosen because the PEF categories employed a mixture of mid- and endpoint methods. Therefore more established midpoint categories have been used instead.

A more detailed overview and discussion of the impact categories selected for this study is provided in Appendix A3.9.

Table 3.4: Summary of relevant impact categories

Impact category	Abbreviation	Indicator and unit
Climate change	GWP	Greenhouse gas emissions GWP100 in CO_2 eq (including carbon feedbacks)
Energy consumption	CED	Cumulative energy demand in MJ: non-renewable (fossil and nuclear) and renewable
Acidification	AcidP	Acidification potential in SO_2 eq
Eutrophication	EutroP	Eutrophication potential in PO_4^{3-} eq
Photochemical ozone formation	POCP	Photochemical Ozone Creation Potential POCP in NMVOC eq
Ozone depletion	ODP	ODP in R11 eq
Ionising radiation	IRP	Ionising radiation potentials in U235 eq
Particulate matter	PMF	Particulate matter formation in PM2.5 eq
Human toxicity, cancer and non-cancer	HTP	Comparative Toxic Unit for Human Health in CTUh
Ecotoxicity, freshwater	ETP_FA	Comparative Toxic Unit for ecosystems in CTUe
Resource depletion - minerals and metals	ARD_MM	ADP ultimate reserves in Sb eq
Resource depletion – fossil energy carriers	ARD_FE	ADP fossil in MJ
Land use	LandU	Land occupation in m^2 *a
Water scarcity	WaterS	Scarcity-adjusted water use in m^3

Note: Shorthand abbreviations as used in this study for summary of results

3.1.5.2 Relevance and importance of different impacts

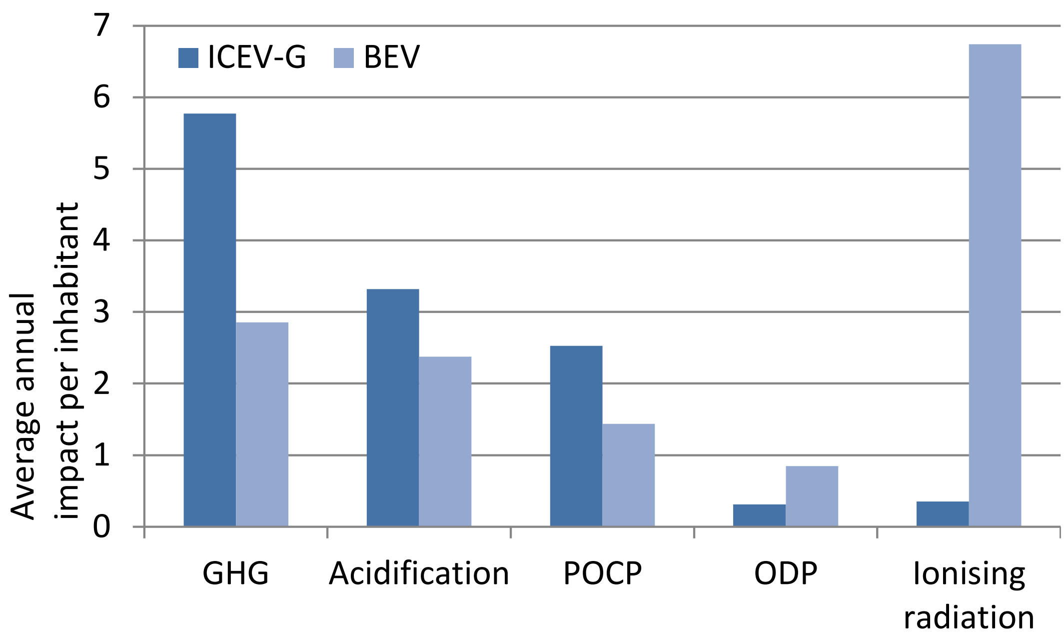
Even though great care was taken in selecting the impact categories documented above and also conducting the life cycle inventory, differences in relevance and robustness of the impacts have to be acknowledged. Interpretation of results should therefore consider the robustness of the impact category in respect to methodology and available data for quantification, and also the relevance of this impact category in respect to road transport's contribution to the overall impact. The following discussion has no direct influence on the results and selection of impact categories; it is intended to provide a better understanding of the relevance and importance of different impacts for interpretation of the results.

A discussion of road transport's contribution to different impacts or selected emissions in Europe has already been provided in section 2.2.3.1 above. An alternative option to formalise this assessment is to undertake a normalisation step, which means "*…calculating the magnitude of category indicator results relative to reference information*" (ISO14040, 2006). This usually puts environmental impacts into perspective on a comparable basis. One common way of normalisation is to divide the results by one person's respective average share of all emissions in one year. Normalisation, however, is only an optional LCA element within the ISO framework and is not undertaken as part of this study, apart from the example below for this section.

Figure 3.2 shows (for illustration purposes here only) the lifecycle impacts calculated in this study for a lower medium passenger car in 2020 (Baseline scenario), normalised by dividing the result by the average annual impact which an EU inhabitant has in that impact category. A normalised result of one thus means that the impact for the vehicle life is as high as the total annual impact of one average EU inhabitant. This reveals if road transport vehicles actually have a relevant share on the total impact in the EU in the respective impact category.

The results clearly show the high relative significance of greenhouse gas emissions. The life-cycle impacts of a car in 2020 are almost six times the average annual impacts of EU inhabitants for the gasoline and almost 3 times the average annual impacts of EU inhabitants for a battery electric car. Normalised impacts of the lower medium passenger car also show the relevance of Acidification Potential and POCP. These are about three times the average annual impacts of an EU inhabitant.

Figure 3.2: Life-cycle results for lower medium passenger car 2020 (Baseline scenario) normalised by average impact per EU inhabitant for one year



Note: LCA results from this study, normalisation based on (Sala, Benini, Mancini, & Pant, 2015). The average lifetime of a lower medium passenger car is 15 years. Provided purely for illustration here.

It is also worth noting that the relevance of impacts may also differ significantly by powertrain and/or fuel type. As the normalised results for ionising radiation in Figure 3.2 show, impacts are low for the gasoline passenger car compared to the normalised impact from a BEV which is close to seven times the average annual impacts per EU inhabitant. This is due to electricity used for charging of BEVs which also includes a share of nuclear power generation.

Existing weighting systems also offer some insights into the perceived relative importance of life cycle impact categories. Such a weighting approach for the Product Environmental Footprint (PEF) has been developed by the European Commission's Joint Research Centre (JRC) through a series of stakeholder consultations and is documented in (Ceruttin, Sala, & Pant, 2018).

Weighting, defined by (ISO14040, 2006) as "*converting and possibly aggregating indicator results across impact categories*", in principle is not ISO-compliant. ISO therefore demands that data prior to any optional weighting should remain available. Weighting is also discussed as a highly critical /contentious aspect within the LCA community, since it is always a value decision and thus represents the subjective understanding of stakeholders. A qualitative discussion of this weighting system, can however, at least offer some insights into the perceived relevance of different impacts.

Table 3.5 shows the robustness and final weighting factors derived for each impact category by the JRC (Ceruttin, Sala, & Pant, 2018). The weighting was derived based on a public survey, a survey with LCA experts and a webinar with impact assessment experts. Robustness has been evaluated taking into account (1) coverage completeness ("… *based on the extent to which the inventory data are available*… "), (2) robustness of data for normalisation (e.g. statistical quality) and (3) robustness of impact assessment methods. Impact categories with perceived robustness in all three parameters would have an overall robustness factor of 1. The final weighting factors then already take into account this robustness and reflect the importance which should be given to the impact; they are scaled to total 100 when all impact categories listed are considered.

Climate change is perceived as the single most important impact category with a weighting factor of 21, which is more than twice as high as the second highest weighting factor of eutrophication. For climate change robustness is also perceived to be outstandingly high. Climate change is followed in final weighting by particulate matter and eutrophication as classical mid-point impacts with a relatively high factor close to 10.

Further impact categories with a high weighting according to (Ceruttin, Sala, & Pant, 2018) are rather resource oriented and included water use[12], resource depletion (fossil energy carries as well as minerals and metals) and also land use. These categories add up to over 70 % of the suggested weighting. It has to be noted, however, that robustness especially for land and water use is assessed to be limited.

Table 3.5: Robustness factors and final weighting factors suggested by (Ceruttin, Sala, & Pant, 2018)

	Our study Abbreviation	Robustness factors	Final weighting factors including robustness
Climate change	GWP	0.87	21.1
Eutrophication	EutroP	0.56	9.5
Particulate matter	PMF	0.87	9.0
Water use	N/A*	0.47	8.5
Resource use - fossil energy carriers	ARD_FE	0.60	8.3
Land use	LandU	0.47	7.9
Resource use - minerals and metals	ARD_MM	0.60	7.6
Ozone depletion	ODP	0.60	6.3
Acidification	AcidP	0.67	6.2
Ionising radiation	IRP	0.47	5.0

[12] Note: In this study water scarcity is being analysed instead

	Our study Abbreviation	Robustness factors	Final weighting factors including robustness
Photochemical ozone formation	POCP	0.53	4.8
Human toxicity, cancer and non-cancer	HTP	0.17	4.0
Ecotoxicity, freshwater	ETP_FA	0.17	1.9

Note: *Not all impact categories exactly match the ones used in this study, e.g. in this study water scarcity is being analysed instead of water use. Weighting factors are therefore only presented here for a qualitative discussion.

A look at just the robustness factors confirms that some factors have a low final weighting mainly due to the identified low robustness. This especially concerns Human and Ecotoxicity, which are potentially perceived as highly relevant, but still lack robust quantification. A grouping by aggregated weighting (excluding robustness) and the robustness factors shows different reasons for the subjective weighting (see Table 3.6):

- Climate change and resource use have a high aggregated weighting AND are perceived to be equally robust.
- Human- and Eco-toxicity as well as water and land use have a high aggregated weighting, but are perceived to be less robust. Concerns regarding robustness have especially been voiced in respect to Human- and Eco-toxicity.
- ODP, particulate matter and acidification are perceived to be robust but have a medium to low weighting
- Eutrophication, ionising radiation and POCP are finally perceived to be of limited robustness AND also a medium to low weighting

The perceived combination of high relevance and robustness for climate change may at least partly explain why many vehicle studies today solely concentrate on greenhouse gas emissions. In addition, the actual impacts resulting from the potential impacts assessed by the mid-point categories (and in particular any impacts of individual air quality pollutant emissions relating to human health) will be highly influenced by exposure levels – i.e. the point of emission. This location-based aspect (e.g. exhaust tailpipe emissions in urban areas are particularly harmful) is not generally captured in the LCA approach and is neglected by many mid-point indicators. Also resource use has become an increasing focus of policy studies. Material and energy flows are also the basis of any LCA study and therefore often backed by more accurate (primary) data. In this sense also cumulative energy demand (CED) can be regarded as a rather robust category, though not included in the weighting system developed by (Ceruttin, Sala, & Pant, 2018).

Table 3.6: Grouping of impact categories by aggregated weighting (excluding robustness) and robustness (Ceruttin, Sala, & Pant, 2018)

	Medium/Low aggregated weighting (< 6)	High aggregated weighting (>= 8)
High robustness factor (>=0,6)	Ozone Depletion, Particulate Matter Formation, Acidification	Climate Change, Resource Use / Depletion
Medium/Low robustness factor (<0,6)	Eutrophication, Ionising Radiation, POCP	Human Toxicity, Ecotoxicity, Water Use, Land Use

3.2 Methodology: Background LCI data

Background LCI (Lifecycle Inventory) data includes the main datasets obtained from existing LCI datasets for key materials, activities and energy carriers that are not directly calculated in this project. These include mainly impact factors for the production of virgin/primary materials and certain recycled/secondary materials, but also some other products (e.g. agricultural chemicals), capital goods for plant, generic transport impact factors, and impact factors for incineration or landfill, etc.

Table 3.7: Overview of methodology applied for the sourcing and processing of background LCI datasets

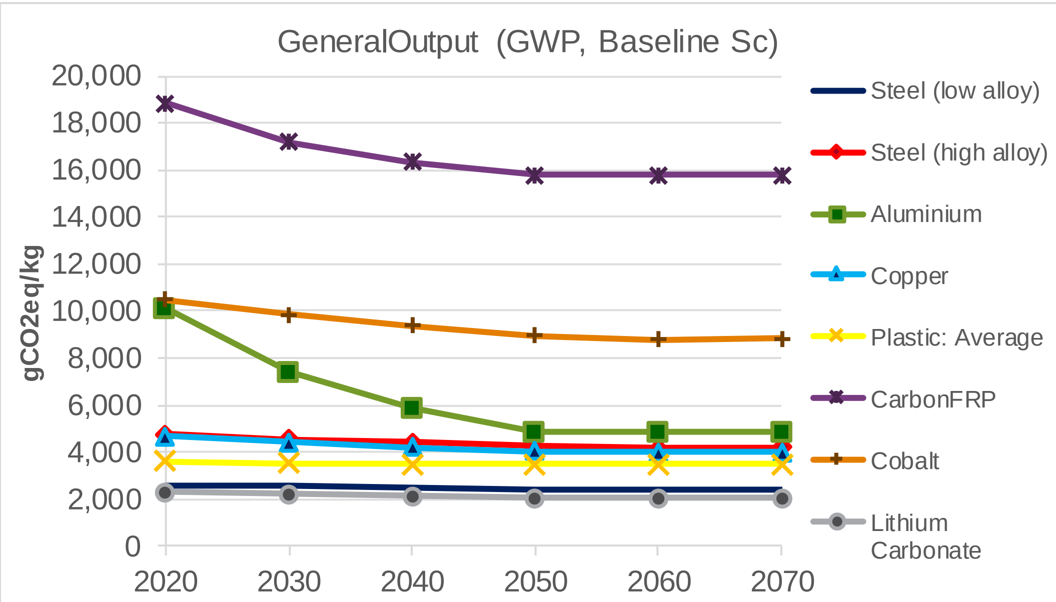
Data type	Summary of methodology applied
Material chain	Primarily used the commonly accepted Ecoinvent database for material production (supplemented with data from GREET where gaps were present);
Temporal considerations	To account for developments up to 2050, decarbonisation of material production (for both virgin and recycled materials, material transformation processes) is included, where relevant: estimated future changes in material production impacts are based on projections for changes in electricity generation mix/decarbonisation (global average, except where specific regional production assumed). More information on the two scenarios used is provided in Section 4.7.
Spatial considerations	For most materials, globally sourced average datasets are used, except for sourcing of aluminium for automotive applications, which is based on European region.

The majority of these factors were sourced from the same common ecoinvent databases, which was supplemented in some cases by data from the GREET model (see Appendix A3 for further information) where data was otherwise not available in ecoinvent. This included materials such as carbon fibre reinforced plastic (CarbonFRP) and certain materials used in battery manufacturing.

Estimates for potential future improvement in the impacts of producing virgin and recycled materials were made based on the share of impacts due to process electricity use by material (extracted also from the background LCI) and the future projections for future relevant regional electricity mix/impacts calculated for this project (see later Section 3.3) – driven by future global decarbonisation objectives. For steel and aluminium, potential future process efficiency improvements based on recent IEA materials analysis[13] were also factored into the future projections. Equivalent information on potential improvements in other material production process was not available.

Trajectories for the GWP mid-point impact category for a selection of key materials under the baseline scenario, calculated using this methodology, are shown in Figure 3.3.

Figure 3.3: Example of Background LCI calculation outputs for the projected future trajectory of GWP impacts for key structural and battery materials for the Baseline scenario



[13] Confidential data provided by the IEA based on analysis for their recent "Material efficiency in clean energy transitions" report, available: https://webstore.iea.org/material-efficiency-in-clean-energy-transitions

3.3 Methodology: Foreground data and methodology for electricity production

Electricity plays a key role within the scope of this project. On the one hand, electricity is used as a fuel for xEVs (i.e. PHEV, REEVs, BEVs and FCEVs), which influences their environmental impacts relating to the vehicle use phase. On the other hand, electricity is used in several parts of the vehicles' upstream chain such as manufacturing of vehicle parts (i.e. including batteries) or resource processing. Furthermore, electricity is relevant in fuel production, including biofuels, where it may also be a co-product from the biofuels production process. It is a key contributor to synthetic (PtX) fuels, which, for example, require electricity for hydrolysis.

For electricity generation, a wide array of different technologies are deployed, which may differ between countries and regions, as well as over time. Moreover, in order to adequately cover the environmental burdens associated with electricity generation, all vehicle lifecycle stages ("cradle to grave"), including all relevant upstream processes and EoL (end-of-life) treatment, are included. Table 3.8 summarises the methodology developed and applied for this project.

Outputs for different electricity chains are based on a combination of results derived from ifeu's Umberto electricity modelling for different generation types, and scenario projections for electricity (generation mix, efficiency, losses, etc) for different EU countries based on two EC energy modelling scenarios. For non-EU countries (Canada, Japan, Korea and USA) and for a world average grid mix, modelling was based mainly on publicly available IEA ETP modelling scenario datasets[14].

Table 3.8: Summary of the methodology applied for electricity chains

Data type	Summary of the applied methodological proposal	
General methodological approach	• LCA with a PCA (process chain analysis)* approach comprising all life cycle stages involved ("cradle to grave"); for the countries in focus modelling of all significant generation technologies on a generic basis with supplementing additional country/technology-specific parameterisation; • Electricity generation mix/composition is based on EU energy system modelling scenarios (see later Section 4.7.1), which incorporates already the demands from electric vehicles (as well as other sectors) in the additional capacity added as a consequence of changes in demand. • For electricity: Average consumption mix of country of origin or EU average mix; output as low voltage electricity.	
Coverage of electricity generation types and fuel types	All relevant (> 5% share) or significant (>5% impact on results across impact categories) technologies / fuels for all spatial / temporal situations. For example, these would at least include conventional thermal power generation (i.e. with the fuel types below) with/without carbon capture and storage (CCS) where appropriate, as well as wind, solar and hydro power generation.	
Fuels for electricity generation	• Coal (hard coal, lignite) • Fuel Oil • Natural Gas • Nuclear fuels (oxidic)	• Waste • Solid biofuels • Liquid biofuels • Biogas / Bio methane
Generation efficiency	Technology-specific considerations and country-specific considerations. Conversion efficiency based on EC PRIMES modelling scenario outputs for different countries / EU28 as a whole.	
Losses	Losses associated with grid integration, transmission, and distribution, based on data from EC PRIMES modelling for the EU, and IEA modelling for non-EU regions, with conversions between Low / Medium / High voltage (e.g. for electricity used in industrial-scale processes) based on data from ecoinvent.	

[14] IEA Energy Technology Perspectives 2017, available here: https://www.iea.org/etp/etp2017/secure/, https://webstore.iea.org/energy-technology-perspectives-2017

Data type	Summary of the applied methodological proposal
Imports/Exports	Included for all countries based on EC modelling datasets
Generation plant production	Included in accordance with general cut-off criteria
Other elements	• Avoidance of double counting • Technology-specific constraints (e.g. generation profile, phase-out of nuclear energy) are accounted for in the EC/IEA scenario datasets.
Temporal considerations	The current (2020) situation is used as a baseline with robust assumptions regarding future developments and corresponding projected future mixes. These future projections are based on EC modelling scenarios (for the EU), and datasets from the IEA (for non-EU regions – CN, JP, KR, US, World).
Spatial considerations	All countries under scope and additional countries that have relevant contributions to the supply chain for all relevant direct (import of electricity) and indirect flows (i.e. as indicated above).
Data sources	Openly accessible data from e.g. EC energy modelling, IEA, EUROSTAT; LCA databases, e.g. ecoinvent or BioEM for background system modelling.

Notes: * Process chain analysis (PCA) assesses every step of a process chain individually, presenting a bottom-up view that results in greater and more complex efforts for data collection than simple input-output analysis (IOA).

3.3.1 The applied Umberto electricity model and derived datasets

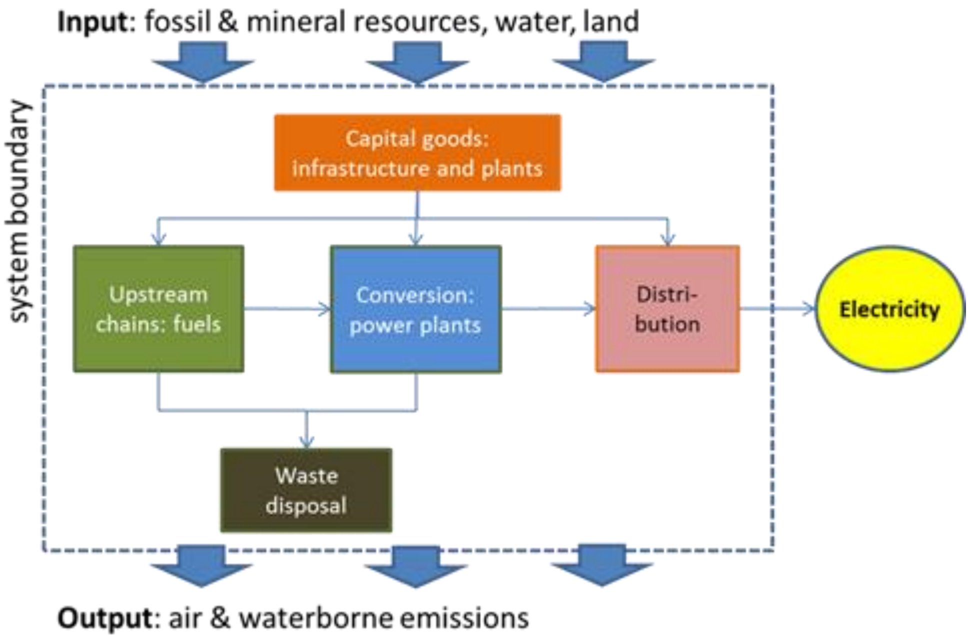
The ifeu Umberto model includes basic power plant types and raw material upstream processes and allows for a flexible approach to all types of network composition, be it national networks, group based or other special scenarios (future or marginal mixes). The system boundary and the major components of the model are shown in a simplified way in Figure 3.4 by (for context, see section 2.2.4.4). A detailed description of the ifeu Umberto electricity model can be found in Appendix A4.2.

The intermediary functional unit for electricity is defined as 1 MJ (or 1 kWh) electricity delivered to the grid (pre transmission and distribution), in order to allow comparison of different electricity production options at an equal level. Further downstream, different loss ratios do occur with regard on the specific user of electricity.

A large number of individual data sets for separate cases are calculated end embedded into the overall model to enable high flexibility. The combination of all the individual parameters (fuel and power plant options, geography, fuel type, temporal development and reference tor climate protection scenarios leads to 3,250 single data sets representing distinct cases of electricity production for the EU28 and individual countries (for grid average mix and individual generation types).

Outputs from the Umberto model are subsequently post-processed to include transmission and distribution losses for EU countries, and also combined with data for China, Japan, Korea, US and world (average) electricity mixes from IEA modelling to calculate impacts for these regions.

Figure 3.4: System boundary and components of the applied Umberto electricity model

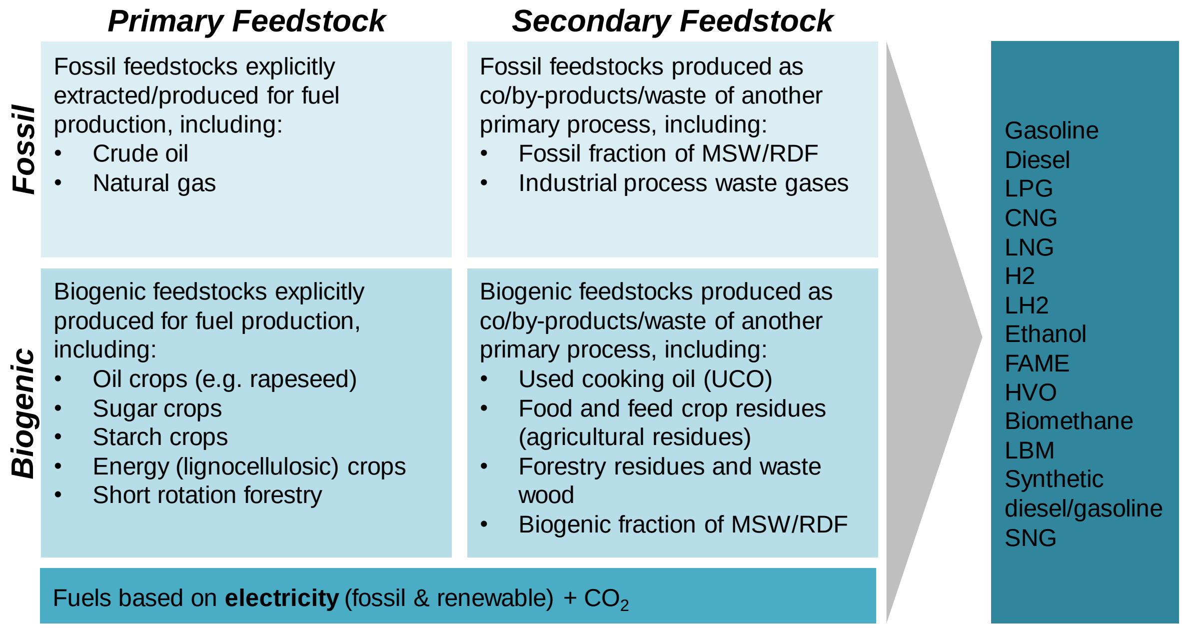


3.4 Methodology: Foreground data and methodology for liquid and gaseous fuel production

3.4.1 Scope and system boundaries

The scope of the LCA methodology applied to liquid and gaseous fuels is limited to a "Well-to-Tank" (WTT) approach, including the extraction/cultivation and collection of the feedstock, fuel production and storage/transportation of intermediary products and the final fuel. In this study, 60 fuel chains were modelled, Figure 3.5 provides a high level overview of the feedstocks and fuels represented. In the case of waste and residue feedstocks (termed secondary biogenic and secondary fossil feedstocks in this study), impacts associated with the production of these materials are out of scope, in line with EU regulation. For example, the impacts from forestry operations are not included for fuels from sawdust or forestry residues. However, environmental impacts from diverting these feedstocks from their existing uses (termed counterfactual emissions) are included in the evaluation, both as avoided and additional impacts (See Section 3.4.2.3 for details).

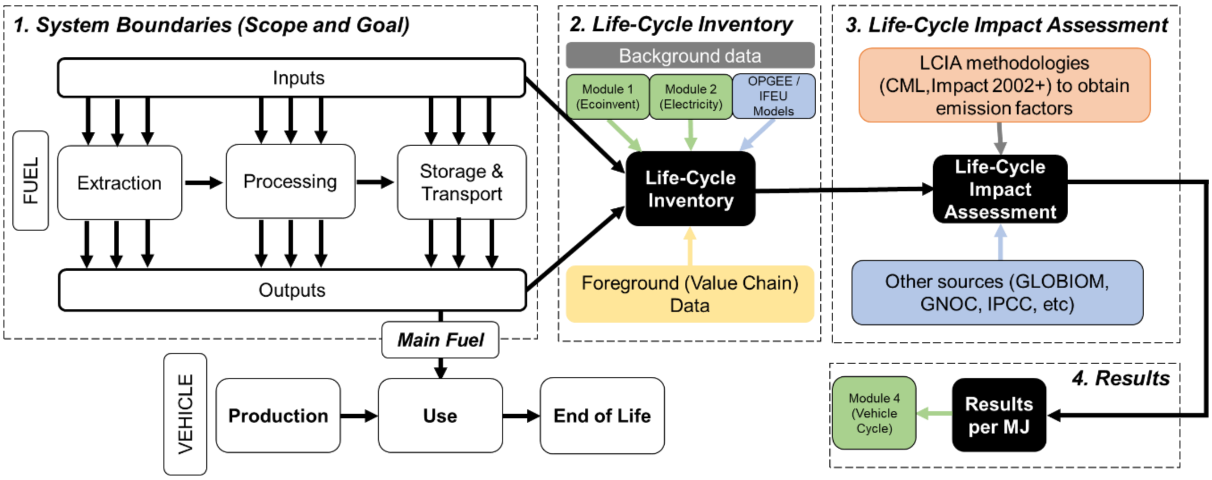
Figure 3.5: Overview of the feedstocks and fuels represented in this study



In addition to WTT impacts, exhaust emissions from vehicles can be broadly characterised as falling into two categories:

1. Those that are emitted at levels at essentially a 1:1 relationship with the amount of fuel (energy) consumed/combusted, as they are directly related to the specific chemical content of the fuel. These include CO_2 emissions and SO_2 emissions, and emissions may be characterised in terms of gCO_2 or gSO_2 per MJ of fuel. It therefore makes sense to gather these all up together also with the WTT emissions, as they are in the same units/are treated subsequently in the vehicle chain in the same way (i.e. energy consumed x emission factor in g per MJ = total emissions). This is also in line with RED II and (JEC (Joint Research Centre; EUCAR; CONCAWE), 2018), in which CO_2 emissions from combustion are added to the Well-to-Tank (WTT) inventory of GHG emissions for fuels. In the case of biogenic fuels and e-fuels, CO_2 emissions from vehicle exhaust are considered null.
2. Those exhaust emissions that do not have a direct correlation with the chemical content of the fuel and/or are further controlled/reduced due to the specific exhaust aftertreatment systems. These are all the other regulated pollutants and emission factors are characterised on a g[pollutant] per vehicle-km basis. These are all included in the vehicle chain (see Section 3.5 and Section 3.6), and are treated differently in calculations – i.e. total emissions = emission factor x vkm

Figure 3.6: Schematic representation of overall (LCA) process implemented for fuel chains.



Notes: Black and grey arrows represent process flows and data inputted for analysis, respectively. Dashed outer boxes illustrate the main methodological steps in the LCA process.

LCA impacts from this part of the analysis are expressed on a **per MJ of final fuel** basis (functional unit). This is done for two reasons: (1) it allows the fuels to be passed forward into the vehicle cycle module, and (2) it allows fuels to be analysed and compared separately and in addition to the results of the overall vehicle lifecycle analysis.

Other elements included in the scope of the fuel chain LCA are:

- **Impacts from capital goods** were included in all fuel chains, primarily based on Ecoinvent datasets. The modelling was structured to allow for sensitivity analysis with or without capital goods.
- **Processing input energy** (e.g. grid electricity, natural gas, lignite, biomass, residual heat, etc.) required for processing fossil or biogenic feedstocks into transport fuels. The modelling allows sensitivity analysis comparing the use of grid electricity to a scenario in which 100% renewable energy would be used.
- In the specific case of fossil fuels on-site **venting/flaring** was included.
- **Multifunctionality: Substitution** was used as an alternative option / sensitivity to the default energy allocation calculation (in line with ISO 14040) for fuel chains which produce more than one product. In a substitution method, impacts from producing the conventional product, equivalent to the co-product produced in the fuel chain, are avoided. A credit is allocated to the system equivalent to the impacts of producing the conventional product. In some cases, the conventional, displaced product is also modelled within the methodology, e.g. conventional diesel and gasoline. Therefore, the impacts up to the point of production, modelled within the methodology, are used as the substitution credit. The methodology does not distinguish between market values of co-products. For example, glycerol is a co-product from FAME production, which is assumed to substitute an equivalent amount of conventional glycerol in our methodology. In reality, a possibility exists that all co-produced glycerol is not entirely consumed, due to market saturation. Therefore, credits (and to some extent, additional impacts) given to co-products may be larger compared to reality. Greater detail on the substitution methodology is provided in Appendix A3.7.3. An alternative multifunctionality is also explored: **energy allocation**, as this is the approach employed by some existing EU legislation, e.g. Renewable Energy Directive. A comparison can therefore be made between the substitution and energy allocation methodologies (See also Section 5.5.8).
- **Elements of consequential LCA** were introduced as an alternative option (to the default energy allocation calculation without a counterfactual) to evaluate the impact of diverting secondary feedstocks from their counterfactual use to fuel production. In this method, the environmental impacts from the feedstock's previous use are considered 'avoided' thus generating a credit. However, the impacts associated with replacing that previous use by another means are quantified and added as a burden to the system. The summation of the two provides an environmental impact of the secondary feedstock, termed *counterfactual emissions.* Further information is provided in 3.4.2.3
- **Direct and indirect land-use change** emission and **Soil Organic Carbon** emissions were accounted for in the biogenic fuel chains. Further information is provided in 3.4.2.2.1.

3.4.2 Key LCA methodological choices

Within the consistent framework of the LCA methodology implemented in this study (Section 3.1), the assessment of impacts for fuel chains required a number of specific methodological adaptations, which were based on the literature review and stakeholder consultation. Some of these choices are not fully in line with current policies (e.g. RED II), but were deemed relevant to explore and feed into ongoing methodological discussions about how LCAs could best support environmental impact evaluations for fuel chains. Table 3.9 summarises the main differences in the LCA methodologies implemented for different categories of fuels. These variations in the methodology, as well as variability in the robustness of data across different fuel chains, mean that a direct comparison of all the fuel chains covered in this study does not provide meaningful or reliable results.

Table 3.9: Summary of main characteristics in the LCA methodologies implemented for fuels

Fuel category	Examples	General LCA Approach(1)	Multi-functionality	Counter-factual uses?(1)	Others
Primary fossil (liquid)	Conventional / Non-conv. Gasoline	Attributional	Allocation (crude refining)	No	Crude refining modelled via ifeu
Primary fossil (gaseous)	Conv/Non-conv CNG/LNG	Attributional	Allocation(2) / Substitution	No	Data for non-conventional natural gas from GREET
Secondary fossil (liquid)	Ethanol from industrial gases	Attributional(1)/ Consequential	Allocation(2) / Substitution	No/Yes (1)	
Secondary fossil (gaseous)	MSW-to-SNG	Attributional(1)/ Consequential	Allocation(2) / Substitution	No/Yes (1)	
Primary biogenic (liquid)	Rapeseed FAME	Attributional	Allocation(2) / Substitution	No	LUC values (including SOC) from GLOBIOM N_2O values from GNOC (JRC)
Secondary biogenic (liquid)	Syndiesel from agricultural residues	Attributional(1)/ Consequential	Allocation(2) / Substitution	No/Yes (1)	
Secondary biogenic (gaseous)	Biomethane from manure	Attributional(1)/ Consequential	Allocation(2) / Substitution	No/Yes (1)	
e-fuels	Hydrogen	Attributional	Allocation(2) / Substitution	No	
Electricity(3)	Gas generation	Attributional	Allocation(4) / Substitution	No	

Notes: (1) An option to include/exclude the counterfactual used for the consequential analysis was included in the LCA modelling to aid comparisons on a consistent basis (see Chapter 5). (2) Allocation by energy was modelled as the default in the final analysis, as an aid to provide consistent comparisons in the overall vehicle LCA, with alternative results based on a Substitution approach also provided for most fuel chains (see Chapter 5). (3) Electricity provided here for comparison; methodology handles both specific generation types and the grid mix. (4) Allocation on the basis of exergy content.

3.4.2.1 Fuels from primary fossil feedstocks

3.4.2.1.1 Crude oil extraction and refining

It was originally decided to evaluate crude oil extraction (upstream operations) based on the model produced by OPGEE (the Oil Production Greenhouse gas Emissions Estimator). Practical implementation turned out to be challenging as OPGEE was designed to assess GWP only, so the information available from the model did not allow other impact categories to be comprehensively assessed; nor did it include sufficient details to extract foreground data and use them in combination with background data from other sources such as Ecoinvent. It was therefore decided to use Ecoinvent to model crude extraction. Crude refining operations were based on the ifeu refinery model, which models co-products through an energy allocation based on average outputs.

Two types of crude oil were considered in the ifeu refinery model, a crude oil based on an average mix of crudes fed to a current archetypal European refinery, and a heavier crude mix, including some non-conventional crude. The use of non-conventional crude oil was modelled by adjusting the parameters of the crude in the ifeu refinery model to match the typical physical-chemical characteristics (density and sulphur content) of non-conventional crude. Two types of refinery were modelled, one representing a current archetypal European refinery, and one representing a future European configuration, which assumed that hydrocracking will be a standard process needed to give the refinery sufficient flexibility to process different crudes. Therefore, to model future fossil fuel production (2030), an increasing share of non-conventional fuel, along with an increased proportion of hydrocracking, was used. This future refinery configuration could therefore require a greater amount of hydrogen, however, this may not necessarily increase overall CO_2 emissions, particularly if the hydrogen is produced via electrolysis powered by renewable electricity or via steam methane reforming with CCS, technologies which are increasingly likely to become more cost competitive. Further information on the ifeu model can be found in Appendix A3.7.3.1.

A comparison of the impacts from fossil fuels, as modelled through the ifeu refinery model, with the impacts from the CONCAWE model used in JEC's Well-to-Wheel report,((JEC (Joint Research Centre; EUCAR; CONCAWE), 2018)) was conducted to identify differences in GHG emissions from gasoline, diesel and LPG. The results of this comparison are detailed in Section 5.3.2.6.

Additional transport and storage stages up to the distribution point were modelled using Ecoinvent.

3.4.2.1.2 Natural Gas

Conventional natural gas was modelled using the Ecoinvent dataset, which includes extraction, processing, storage and transport. For conventional natural gas, Ecoinvent datasets for natural gas production in Russia, Algeria and Germany were used. A weighted average data set was constructed, based on the gas mix as reported in from NGVA report (*Greenhouse Gas Intensity of Natural Gas* (thinkstep AG, 2017), where Germany was used to represent production in other EU countries, and Algeria represents non-EU countries excluding Russia[15]. A comparison was made for GWP with the results obtained by JEC to identify potential differences in the modelling and data used (See Section 5.3.2.7).

Since non-conventional natural gas (shale gas) is not modelled in Ecoinvent, data from GREET was used. While GREET builds upon US data, it was considered the best data sources for non-conventional gas for this study, as it allows modelling all impacts. The use of US data does, however, introduce some uncertainty and inconsistency into this fuel chain. Future developments should therefore include the building of EU-based data sets for non-conventional natural gas.

3.4.2.2 Fuels from primary biogenic feedstocks

3.4.2.2.1 Land-use change

Land-use change (LUC) is caused by the conversion of land from an initial state (e.g. forest, savannah, crop field, plantation, etc.) to another state. LUC may also occur in other locations whenever biofuel production diverts biomass (including food and fodder crops) from other uses. As a reaction, other sectors using biomass may trigger more land conversion to produce additional biomass. This market-mediated land-use change (also known as induced or indirect land-use change or iLUC) can only be assessed using global socio-economic models to model the complex interactions between supply, demand and pricing in different sectors of the economy, thus applying the consequential approach to LCA.

Land-use change estimates and resulting GHG emissions were obtained from the GLOBIOM model and added to the corresponding midpoint used at the LCIA stage (GWP). Since GLOBIOM values also included soil organic carbon emissions, these were not further added to emissions from cultivation to avoid double counting.

3.4.2.2.2 Inputs to crop cultivation and field emissions

Impacts from agricultural inputs (fertilisers) and other activities (e.g. tillage, harvesting) were modelled using existing Ecoinvent datasets. These were however customised to replace the N_2O emission factors by the values provided by the GNOC (The Global Nitrous Oxide Calculator), Field N_2O emissions

[15] This approach was necessary as Ecoinvent data sets were not available for gas production in other countries supplying the EU

are significant contributors to the GWP of crops; it was therefore deemed important to include them in the scope of the modelling, GNOC being acknowledged as the best source to estimate such emissions.

3.4.2.3 Fuels from secondary fossil and biogenic feedstocks

When evaluating life-cycle impacts of fuels from secondary biogenic feedstocks, no distinction was made between material which carries no economic value and would otherwise be discarded (usually defined as a waste) and material which has an existing low-value use (usually defined as a residue).

As noted above, the scope for fuels produced from secondary fossil feedstocks include the impacts of diverting that feedstock from an existing use (termed 'counterfactual use') and replacing any useful products (such as heat or power) that it generated. This approach required a number of steps:

1. Identification of the counterfactual use of that feedstock
2. Identification and quantification of useful products produced from that counterfactual use
3. Identification of how that useful products would be alternatively supplied
4. Quantification of environmental impacts from supplying that useful product by an alternative means

Figure 3.7: Approach adopted in this study to calculated environmental impacts of secondary feedstocks

Environmental impact of secondary feedstock	= -	{environmental impact of its previous use}	+	{environmental impact of providing that previous use by another means}

For each feedstock many different counterfactual uses are possible (e.g. agricultural residues such as straw may serve as animal bedding, be left on the field as fertiliser or be burnt for power production), but for the purposes of this study one likely counterfactual scenario was identified and modelled. For manure the counterfactual use is as fertiliser on fields, and for all other feedstocks considered in this study the counterfactual use modelled is combustion for electricity production. Future studies should explore alternative counterfactual scenarios.

For the identification of how products produced from secondary feedstocks would be replaced, and the environmental impact associated with this (points 3 and 4 above), the likeliest substitute was identified (e.g. grid electricity when feedstocks were diverted from power production).

The counterfactual scenario modelled for each feedstock is described in Table 3.10

Table 3.10: Counterfactual scenario modelled for each feedstock

Feedstock	Counterfactual scenario modelled
MSW	Combusted to generate electricity (0.23MJ$_{electricity}$/MJ$_{MSW}$)
UCO	Combusted to generate electricity (0.26MJ$_{electricity}$/MJ$_{UCO}$)
Straw	Combusted to generate electricity (0.22MJ$_{electricity}$/MJ$_{straw}$)
Agricultural residues	Combusted to generate electricity (0.22MJ$_{electricity}$/MJ$_{agricultural\ residues}$)
Forest residues	Combusted to generate electricity (0.23MJ$_{electricity}$/MJ$_{forest\ residues}$)
Sawdust	Combusted to generate electricity (0.23MJ$_{electricity}$/MJ$_{sawdust}$)
Waste industrial gas	Combusted to generate electricity (0.26MJ$_{electricity}$/MJ$_{Waste\ industrial\ gas}$)
Manure	Used on field as fertiliser (Note: the digestate resulting from anaerobic digestion of manure is documented as an excellent fertiliser with equal or even higher nutrient content per mass than unprocessed manure. Therefore, no additional emissions are attributed to biomethane from manure to compensate for the missing fertiliser).

Avoided and additional environmental impacts from the use of secondary feedstock were modelled using Ecoinvent datasets (as for all other background data in this study), except in the case where electricity production was the counterfactual use. For this, impacts were taken from the part of the LCA modelling dealing with electricity production and were based on the average grid electricity modelled within this study, which varies over time. Therefore, in the tool the environmental impacts from replacing the existing use of a secondary feedstock is represented by the average impacts of the product which would replace it. Further work could investigate the marginal impacts of replacing the existing use of a secondary feedstock.

3.4.2.4 E-fuels

All e-fuels have a common initial step: hydrogen production from an electrolyser. In the default scenario, all e-fuels, except for hydrogen produced by electrolysis, are assumed to be produced with renewable electricity. This includes the electricity requirements for the electrolyser to produced hydrogen, and all subsequent process steps (e.g. compression, liquefaction). For the H2-Electrolysis fuel chain, two alternatives are modelled, in the default scenario, one using grid average electricity and one using renewable electricity for the fuel production steps, i.e. electrolyser and compression. Any electricity requirement for downstream transportation, storage and distribution is assumed to be grid average electricity for all e-fuel chains in the default scenario. Impacts from electricity use are based on the electricity chains modelled in this study, as described in Section 3.3.

For synthetic fuels containing carbon atoms (methane, syndiesel and syngasoline), the hydrogen must be further reacted with CO_2. The CO_2 is assumed to come from a waste stream that would have otherwise been emitted to the atmosphere. Therefore, no environmental impacts are associated with the emission of CO_2 from the combustion of e-fuels. The environmental impacts associated with the waste CO_2 capture, compression and transportation are included. There is currently no agreed methodology to calculate the GWP impact of fuels produced using waste CO_2 in the EU. If the waste CO_2 accounting approach used in Module 3 was adopted to calculate the GHG intensity of e-fuels under a transport decarbonisation policy, it would be important that the primary producer of the fossil CO_2 continues to account for it as an atmospheric release. This avoids both the primary producer of the CO_2 and the e-fuel producer claiming CO_2 savings. Only one CO_2 capture scenario is assumed in the methodology. Including additional CO_2 capture scenarios could be an area for future development and work.

The downstream transportation and distribution of e-fuels are modelled in the same way as other fuel chains producing the same end-fuel, for example the downstream transport of e-fuel syndiesel from the plant to the consumer is the same as that of bio-syndiesel.

Table 3.11 outlines the electricity requirements in both production and downstream transportation and distribution (T&D), on a MJ of electricity per MJ of final fuel basis. All e-fuel chains have a common step: hydrogen production from electrolysis. For the other e-fuel chains further reaction of the hydrogen with a carbon source is required. Therefore the H_2-Electrolysis chain has the lowest electricity requirement, as all other chains include this process but require further energy input and have additional efficiency losses in further processing into fuel.

Table 3.11: Electricity requirement for production and downstream T&D of e-fuels and hydrogen

Fuel chain	Electricity use in production (MJ/MJ final fuel)	Electricity use in downstream T&D (MJ/MJ final fuel)
Hydrogen	1.56	0.04
Liquid Hydrogen	1.86	0.01
SNG	2.11	0.02
Liquid SNG	2.15	<0.00
Syndiesel	3.13	<0.00
Syngasoline	6.65	<0.00

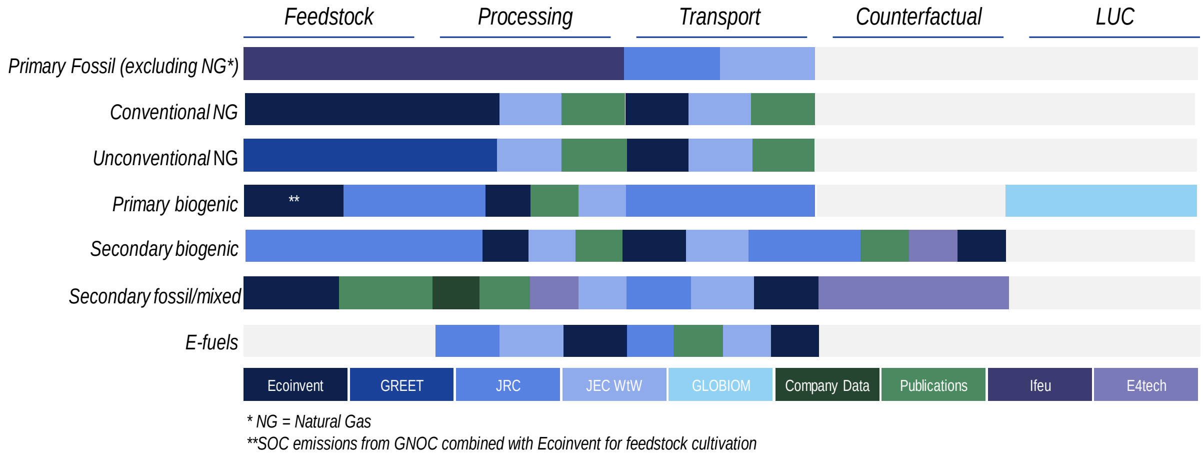
3.4.3 Foreground data

Given the large number and diversity of feedstocks and fuels covered in the fuel chain modelling as shown in Figure 3.8, a combination of datasets from different origins was required. No single complete dataset, which contained all inputs and outputs for all 60 fuel chains, was publicly available. Furthermore, many datasets and lifecycle inventories which are available are limited to assessing GHG emissions so do not contain all the data needed for an LCA such as this one, which is considering a range of impact categories.

Most conventional fossil and biofuels are well documented in LCA datasets and other mainstream studies. However, this is not the case for less commercially mature fuels such as synthetic fuels, secondary fossil fuels or e-fuels. In some instances, single peer-reviewed publications for a lifecycle stage, e.g. syngas production from wood feedstocks, were combined with other datasets for other lifecycle states, e.g. JRC's data on transportation of a liquid fuel (Edwards, et al., 2019), which also provides input data used to define the default values of EU RED II. This can affect the consistency of the modelling, and thus the results, as the studies may not give enough detail to ensure that the product exiting one lifecycle stage has the same characteristics e.g. LHV, pressure, moisture content etc as that assumed in the next stage. This issue is particularly acute where more than one dataset was required to model a single life-cycle stage, e.g. synthetic fuel production from Fischer-Tropsch of syngas uses the product slate and process efficiency provided by the JEC in combination with input and output flows provided by a single peer-reviewed publication. All assumptions which were used to manipulate data and allow combination of data sets from different sources have been documented in the model.

Figure 3.8 provides a summary of the number of foreground data sources required to model the 60 fuel chains in the study, broken down by feedstock category. The sources shown in the diagram represent the total required to model every fuel chain within that feedstock category and lifecycle stage, as opposed to the number required per fuel chain in that category. For example, to model ethanol from wheat, three data sources were joined together to form the chain (Ecoinvent for cultivation data, JRC for processing and transport data and GLOBIOM for land use change), compared to a total of six data sources required to model all primary biofuel chains. For a complete disaggregation of sources required to model each of the 60 fuel chains, accompanied by detailed discussion of this, refer to Appendix A3.12.

Figure 3.8: Summary chart of the different foreground data sources used in in the modelling of fuel chains



The most important considerations regarding foreground data used in the fuel chain modelling are:

- **Primary biogenic feedstocks**: Foreground data for crop cultivation and forestry were extracted from Ecoinvent, as these can be used to model all midpoint impacts. Furthermore, they allow some customisation in order, for example, to remove or modify specific values such as land-use change emissions (which are added separately, based on GLOBIOM) or field emissions.
- **Crude chains:** Ecoinvent provided crude extraction data, which included a mix of crudes from on-shore and off-shore extraction sites in UK, Norway, Middle East, Nigeria, other African countries and Russia. Crude refining data were used in the ifeu refinery model, but also

originates from Ecoinvent datasets. Ecoinvent datasets were also used for transport and storage.

- **Conventional natural gas:** a weighted average of natural gas production (extraction, processing, transport, storage and distribution) based on an EU gas mix was used based on Ecoinvent data.
- **Non-conventional natural gas:** datasets on extraction and processing come from the GREET model and assume shale gas. The rest of transport and storage is modelled similarly as with conventional natural gas using Ecoinvent data.
- **Secondary biogenic, fossil and mixed feedstocks:** generally, a greater number of data sources were required to model these chains, particularly for those in early stages of commercialisation, e.g. SNG from MSW and synthetic fuels from MSW and residues. Several data sources (including Ecoinvent, JRC and peer-reviewed publications) were required to model a complete chain, and, in some cases, even multiple were required within a single lifecycle stage (e.g. FT step for synthetic fuels). Notably, for MSW fuel chains, three sources were required to model the feedstock collection life-cycle stage, which reduced the robustness of the results obtained for these chains. Additionally, for syngasoline chains specific datasets were not available so the data for syndiesel had to be adapted for syngasoline.
- **E-fuels:** similar to secondary feedstocks, these processes are relatively novel, with limited publicly available data. Impacts from electricity production were taken from the electricity chain modelling described in Section 3.3. The additional processing to turn hydrogen into synthetic fuels and other transport/storage stages were aligned with other synthetic fuel chains (secondary feedstocks), hence from multiple data sources.

3.4.4 Temporality for fuel chains

Temporality in fuel chains is addressed only through the variations in the electricity mix, which is used as process energy in all fuel chains. For chains with an intensive electricity use, important temporal variations in impacts can be observed as the electricity mix decarbonises and moves towards a higher share of renewables, while decreasing fossil and nuclear shares (see Section 5.3.2.5).

Temporal variations in the electricity mix also affect the impact of fuels generating co-products substituting electricity. In such case, the progressive reduction in the GWP impact of the average European grid will reduce the GWP substitution credit obtained from co-products, thus increasing the GWP impact of the fuel over time, all other things equal. Similarly, fuels diverting feedstocks from electricity production get an additional burden, due to missing electricity production being compensated through the grid. In such case, the burden added to the fuel chains for the diversion of feedstock (e.g. municipal solid waste) from electricity production, which will need to be replaced by grid electricity, will decrease over time, thus decreasing the GWP impact of the fuel at the same time.

No temporal variation in the foreground data was included in the application of the methodology, due to a lack of robust data. Therefore, the same quantity of inputs and outputs for each fuel chain are maintained over time. This means our methodology does not currently capture potential process or technology improvements (though these could be added at a later date should data become available).

3.5 Methodology: Foreground data methodology for vehicle specifications and operational emissions

Impacts resulting from the vehicle life cycle are highly dependent on assumptions on key vehicle characteristics. It was therefore important to use consistent and robust approaches to characterising different vehicle types and powertrain options and their operational impacts. A key criterion for meeting the goal and the scope of this project is to compare *equivalent* vehicles (which is not necessarily the case for specific models available on the market), and the developed methodology sets out how this can be achieved. Our applied methodology for the foreground data for the vehicle specification and use profiles is summarised in Table 3.12 below, and later Section 4.7 provides a summary of some of the key foreground data inputs/assumptions. Further details on the applied methodology are also provided in Appendix A3.13 of this report, and more information on the specific foreground data assumptions is provided in Appendix A4.3.

Table 3.12: Methodology applied for vehicle specification, covered emissions and use profiles

Data type	Summary of methodology applied
General vehicle specifications	Define equivalent reference ICE vehicle for vehicle type/segment, based on current market norms and characterise other powertrains relative to these. Use scaling factors to define sizing of key components for alternative powertrains (e.g. motor, battery) based on market and engineering analysis, and performance criteria.
Vehicle unladen mass and composition	Define EU average mass and material composition for baseline ICE representative vehicle body types based on pre-existing sources/analyses, normalised to current market averages, where appropriate. Define variations for different powertrain types based on defined sizing /composition of key components.
Energy storage and fuel cells	Utilise a more detailed approach for characterising electrical energy storage based on different potential battery types (and hence material composition) and assumptions on future energy density improvements (in Wh/km). Energy storage sizing calculated based on vehicle efficiency and range assumptions (with sensitivities on these), and battery reserved state-of-charge (SOC) share by powertrain type. Storage mass based on energy density (Wh/kg) projections for batteries (with sensitivities), and similarly for storage of gaseous fuels. Frequency of storage replacement are accounted for based on cycle life / hours life and operational use. End-of-life accounting considers implications of 2nd-life batteries via estimated volumes, processing and credits. Fuel cell sizing based on current and projected future changes in power density (W/kg), and relevant scaling factors relating to peak power requirements (i.e. to account for potential buffering with battery storage).
Energy consumption	Baseline performance assumptions for conventional powertrain types based on current models and estimates of relative performance for a range of powertrain types. Real-world profiles for EU average energy consumption were developed, calculated from regulatory cycle-based values. For LDVs these were based upon LDV CO_2 monitoring datasets, and EC JRC conversion/correlation factors for converting NEDC to WLTP to Real-World (the latter including EU average impacts of a range of real-world operational effects, including also auxiliary use for heating/cooling) (Ricardo Energy & Environment et al., 2018). Regulatory energy consumption for HDVs for different powertrain types were estimated in part based on Ricardo simulation analyses using VECTO and the relevant vehicle regulatory cycles, and adjusted to real-world based on average mileage shares by road type. Estimation of variation in (real-world) energy consumption by road type based on speed-energy consumption equations (e.g. COPERT or derived from simple simulations based on VECTO cycles for new HDV powertrain types), average EU activity shares by road type (where available). Charging losses accounted for within energy consumption values (i.e. as in type approval), and not separately. Simple dynamic adjustments made based on change in vehicle mass (e.g. varying battery mass or vehicle loading factors), using the derived estimates for the variation in fuel consumption by loading factor from VECTO simulation modelling or COPERT speed-energy consumption equations. Simple sensitivities applied for LDVs on the effects of extreme ambient temperatures (i.e. from +35 ^{o}C to -10 ^{o}C) on vehicle energy consumption.

Data type	Summary of methodology applied
Fuel split for dual-fuel / PHEVs	Based on the fixed WLTP utility curve for LDVs (applied to real-world range calculations), or a specific share for a given duty/drive cycle for HDVs (based on direct link with km electric range, with optional prioritisation of driving to urban roads). Sensitivities applied to explore potential variation due to different behavioural (e.g. charging frequency) or duty-cycle effects/operational restrictions.
Vehicle direct emissions	Tailpipe emissions of CO_2, SO_2 are based directly on carbon and sulphur content of the fuels and energy consumption; separate tracking for fossil and biogenic/sequestered carbon content is included. Other (including non-tailpipe) emissions are based on existing inventory methods (mainly based on COPERT speed-emission equations) for Euro 6d / VI standards for vehicles, average EU activity shares by road type. Tyre/brake/road-wear PM emissions are also included. Simple dynamic adjustments also made based on change in vehicle mass (e.g. varying battery mass or vehicle loading factors), using the derived estimates for the variation in fuel consumption by loading factor from the COPERT speed-emission equations.
Activity and lifetime	Age-dependant activity (annual km) profile based on the most recent evidence on this from recent studies and modelling, calibrated to total lifetime activity/years. EU average activity split by road type, with sensitivities on this to account for regional variations.
Temporal considerations	Accounting for future improvements/changes in mass of the vehicle as a whole (linked also to changes in material composition) and of different components (e.g. via energy or power density), and projections for future vehicle energy consumption.
Spatial considerations	Accounting for EU level variability in vehicle efficiency, emissions and mileage by road type, plus sensitivities to investigate the degree of variability in these by country or duty cycle. Spatial considerations also capture the impacts due to variation in regional electricity mix and, in a more limited way, the variations in average ambient temperature between regions for LDVs.

3.6 Methodology: Foreground data and methodology for vehicle manufacturing, maintenance and end-of-life

Impacts of the vehicle equipment cycle are significant especially for alternative powertrains and in respect to a number of impact categories beyond GWP. As such, a consistent and sound approach to assess differing components between vehicle types (especially batteries) was developed. The methodology for the modelling of vehicle production, maintenance and disposal is summarised in Table 3.13 below, with more detail on the end-of-life aspects provided in the subsection 3.6.1. Further details on the applied methodology are also provided in Appendix A4.3 of this report.

Table 3.13: Methodology applied for the modelling of vehicle production, maintenance and disposal

Data type	Summary of methodology applied
Material chain	Primarily used the commonly accepted Ecoinvent database for material production (supplemented with data from GREET where gaps were present); estimate future changes in material production impacts based on projections for changes in electricity generation mix/decarbonisation (global average, except where specific regional production assumed).
Vehicle manufacturing	Consider differentiated material compositions, material losses, process energy and auxiliary materials for generic vehicles in a modular/component-based way (see Table 3.14). Materials and energy are directly linked to the material chain and energy chains derived in this study.

Data type	Summary of methodology applied
Vehicle maintenance	Estimates based on in-service replacement of key parts/consumables, including: tyres, battery, exhaust/aftertreatment; coolant, oil, AdBlue, screen wash, other liquids.
Vehicle EoL	PEF (Product Environmental Footprint) Circular Footprint formula/methodology applied for vehicle (excl. battery) and for xEV batteries. Materials and impacts from battery recycling based on GREET data and methodologies. End-of-life accounting considers implications of second-life batteries, plus sensitivities.
Temporal considerations	Accounting for future changes in material composition of vehicles (e.g. due to light-weighting) and for increased energy density or different cell chemistry of batteries Projections for future cell manufacturing energy consumptions and different electricity mixes Decarbonisation of material production is included, where relevant, which impacts on both vehicle/battery manufacturing, as well as end-of-life recycling credits. End-of-life treatment impacts, and energy recovery credits factor in changes in future electricity impacts
Spatial considerations	Vehicle assembly electricity split based on EU production, imports. Account for different electricity mixes if country of origin for battery manufacturing. Assess the impact of varying future EU battery cathode, cell and pack production.

Table 3.14: An overview of the modular approach applied to vehicle production configurations

Component	ICEV Liquid	ICEV Gaseous	HEV	HEV -ERS	PHEV or REEV	BEV	BEV -ERS	FCEV	FCEV -REEV
Glider	Y	Y	Y	Y	Y	Y	Y	Y	Y
Trailer system (artic lorries only)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Engine (ICE)	Y	Y	Y	Y	Y				
Transmission (1)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Exhaust system	Y	Y	Y	Y	Y				
Aftertreatment (2)	Y	Y	Y	Y	Y				
Fuel tank	Y	(3)	Y	Y	Y				
Gaseous fuel storage (4)		Y						Y	Y
Motor			Y	Y	Y	Y	Y	Y	Y
Battery (traction)			Y	Y	Y	Y	Y	Y	Y
On-board charger					Y	Y	Y		Y
Power electronics (5)			Y	Y	Y	Y	Y	Y	Y
Pantograph for dynamic charging system				Y			Y		
Fuel cell system (6)								Y	Y

Notes: (1) Transmission requirements vary depending on the specific configuration and type (e.g. single gear-ratio common for BEVs); (2) Different for petrol, diesel and for gas vehicles; (3) also needed for dual-/bi-fuel vehicles; (4) Different types - e.g. CNG, LNG, LPG, hydrogen; (5) Inverter, Boost converter, Power control unit, Wiring harness, Regenerative braking system, HVAC heat-pump (6) Fuel cell stack, Fuel cell peripherals.

3.6.1 Vehicle end-of-life

Approaches to End-of-life (EoL) modelling have been broadly discussed within the LCA community in recent years and while there is still no overall consensus on the single best approach, there is a growing trend towards using the PEF (Product Environmental Footprint) 'Circular Footprint Formula' (PEF CFF) (JRC, 2018a)[16] methodological approach in the EU. From a legislative context, the question surrounding treatment of EoL is whether the focus is more on promoting recycling, or use of secondary materials. The PEF CFF has been developed, in part, to account for the variation of this focus for different materials, as well as to account for other factors, such as differences in the quality of input and output materials. We therefore used the PEF CFF as the basis for the EoL accounting for both vehicles and batteries.

An additional element developed for the methodology in this project is the treatment of second-life / repurposed xEV batteries. In this case, the applied end-of-life (EoL) accounting for batteries considers the implications of second-life batteries using a credit applied based on assumptions for the avoided use of an equivalent new energy storage battery (as a fraction based on the average situation – i.e. assumed % lifetime of new batteries x % share of EoL batteries replacing new batteries x remaining battery %SOH (State-of-Health) at the end-of-life in the vehicle).

[16] Further information is available here: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

4 Application of the LCA methodology

This chapter provides a summary of the development of the application framework, led by Ricardo, to provide the results for Task 4 of the project, and a summary of some of the key foreground data assumptions used in the vehicle LCA modelling.

4.1 Overview of methodological approach for the application

Figure 4.1 provides a high-level overview of the modular LCA calculation approach for the application of the developed LCA methodology for the project. The modular approach has allowed for the calculation of results from the project in a systematic way. A summary of the different components in this modular approach is provided below. More detailed explanations of the individual framework modules are provided in the following subsections, with additional information in Appendix A4 also.

(0) Underlying background LCI datasets: Ecoinvent is the main background LCI dataset used in the project calculations. It has been supplemented with additional data from the GREET (2019 update) model (produced by the US Argonne National Laboratory) to fill gaps, mainly for the battery LCA calculations.

(1) Module 1, Generic background data: The background LCI database contains the main data inputs provided from the background LCI databases (i.e. ecoinvent, GREET, etc.) as well as other data inputs / assumptions used to further transform these. The main transformations include the development of a timeseries of estimated future impacts for materials used in battery and vehicle manufacture, based on scenario projections for electricity decarbonisation from EC and IEA modelling. These are subsequently passed onto the other LCA modules. Outputs are mostly in units of impact per kg material (others include MJ of energy, kWh electricity, etc).

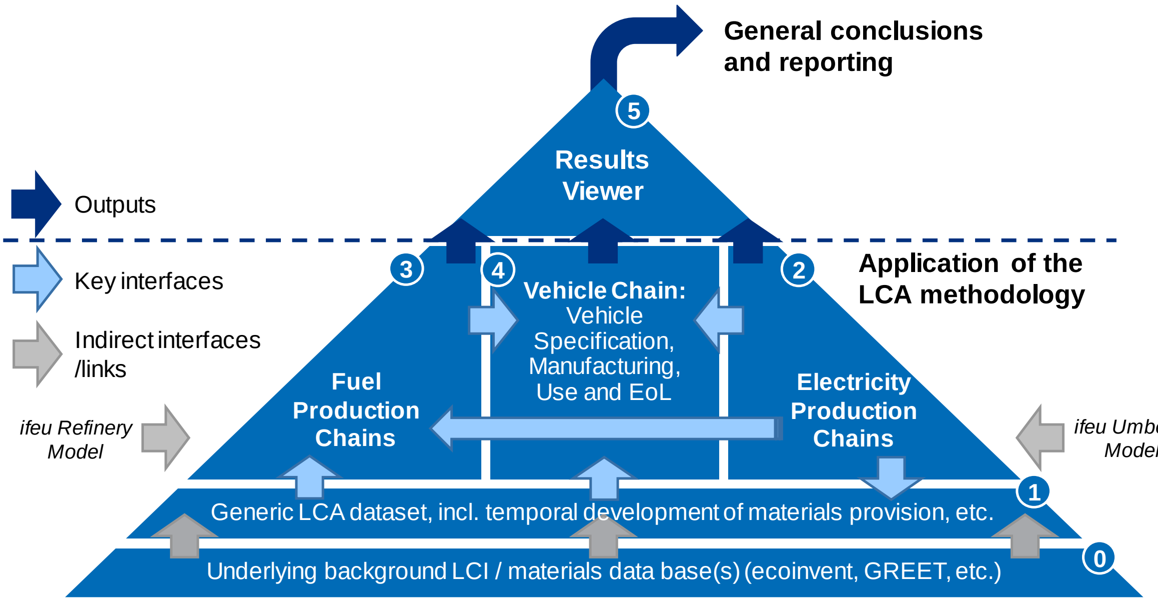
(2) Module 2, Electricity Chains: The electricity production module contains the main data and calculations for the electricity chains. Key inputs include EU electricity modelling scenario data supplied by the Commission (from modelling for the EC's Long-Term Strategy, based on PRIMES/PRIMES-TREMOVE), emissions outputs from ifeu's Umberto electricity model, and supplementary impacts data from the background data module. Output are in units of impact per kWh or MJ of electricity consumed (low voltage).

(3) Module 3: Fuel Chains: The fuel module calculates the impacts for fuel chains from well-to-tank (WTT), including an inventory (LCI) of consumption and emissions on the basis of modules 1 (background data) and 2 (electricity inputs), as well as other external data, which primarily included JEC's most recent WTT/WTW reports, JRC (2017 Solid and gaseous bioenergy pathways: input values and GHG emissions) and Ecoinvent. The JRC (2017) study computes the RED II typical and default values for renewable fuel chains. Other key inputs into module 3 include agricultural data (e.g. fertiliser production, seed production, machinery, etc.), electricity production (module 2) output data, ifeu's refinery model for fossil fuel chains, GREET for non-conventional natural gas, LUC evaluations from GLOBIOM (including SOC), fertilisers emissions (GNOC) and a range of supplementary inputs/outputs data from the background LCA module (module 1). Outputs are in impacts per MJ of final fuel.

(4) Module 4, Full Vehicle Chain: This module contains the main vehicle cycle data and calculations, including also the data outputs from the other modules, to produce the final complete LCA results. This module also includes an extensive range of configurable data settings (with fixed and variable vehicle and other parameters), scenario datasets (e.g. based on EC modelling scenarios, as above), and sensitivities (based on some of the variable parameters) – see later Section 5.5. Outputs are in either total impact units, or units of impact per vehicle- or tonne-km.

(5) Module 5, Results Viewer (available alongside this report): The 'Results Viewer' module contains the final outputs from the overall vehicle LCA calculations, which are imported into it in a static flat database-style format. The module contains a range of configurable summary tables and charts used to interpret and present the findings from the analysis.

Figure 4.1: Overview of the LCA application framework and key data flows



Notes: Data calculation/flows are carried out in the indicated order from 0 (background LCI) to 5 (results).

4.2 Background LCI database (0) and generic background LCA dataset (1)

The background Module 1 generic LCI database contains the main data inputs provided from the background databases (i.e. primarily ecoinvent, with gaps filled mainly from GREET, etc.) as well as other data inputs / assumptions used to further transform these. The key additional external inputs relate to the assumptions used to develop the timeseries estimates for the change in impacts for different materials used in vehicle and battery manufacturing that are subsequently passed onto the other LCA modules. These include inputs from Module 2: Electricity Chains for different regions, and input data assumptions for improved steel and aluminium process efficiency based on datasets supplied by IEA based on their analysis of materials (IEA, 2019).

The calculation of future impacts in materials production/processing were implemented based on data extracted from Ecoinvent and GREET on the electricity consumption used in the production of the materials, and relevant regional electricity mix/impact trajectories.

The output from this module are imported into the other relevant LCA calculation framework modules as shown in Table 4.1.

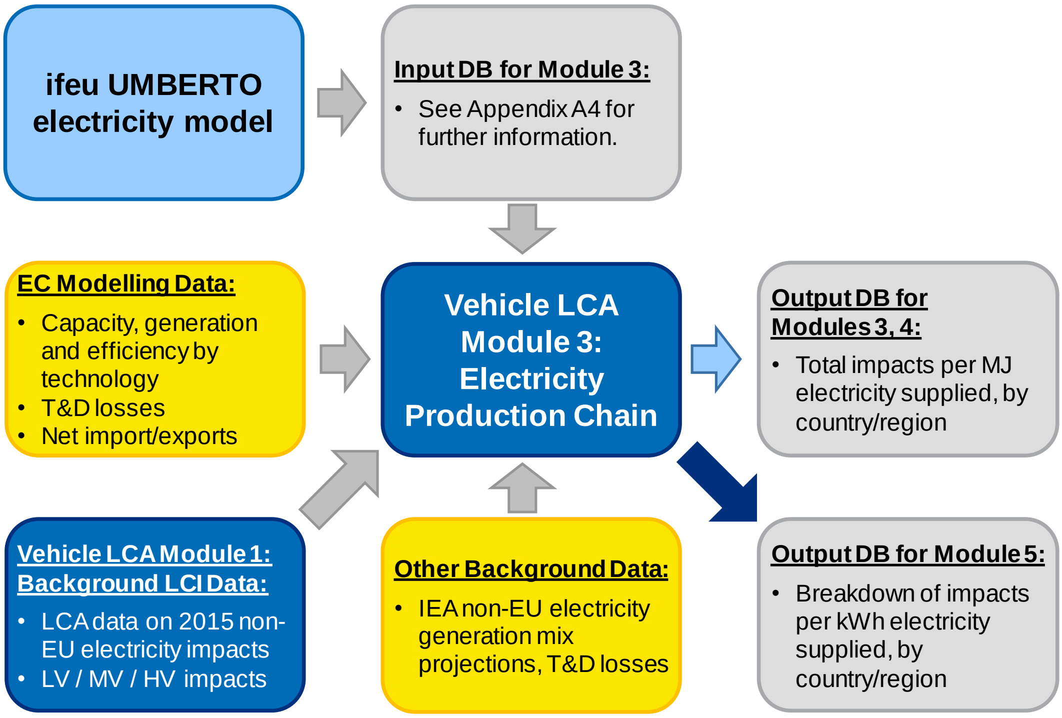
Table 4.1: Key inputs and outputs for Module 1

Key Inputs to Module 1:
• From Module 0: Underlying background LCI data from ecoinvent database
• Additional background LCI data from other sources (e.g. GREET) to fill gaps
• Other data and assumptions (e.g. from IEA) used to develop time-series for emissions/impacts
Key Outputs from Module 1:
• *To Module 2*: Timeseries background LCI datasets relevant to electricity production (e.g. also global and regional average electricity production impacts per kWh electricity consumed)
• *To Module 3*: Timeseries background LCI datasets relevant to fuel production
• *To Module 4*: Timeseries material and other background LCI data impacts relevant to vehicle cycle

4.3 Electricity production chain module (2)

The electricity production module contains the main data and calculations for the electricity chains, and is fully disaggregated by country / region and by electricity generation type. Key inputs to this module include EU electricity scenario data (from EC energy modelling), emissions/impact mid-point outputs from ifeu's Umberto electricity model (see Appendix A4.2 for further information), and supplementary impacts data from the background LCA module (i.e. 2015 electricity impacts for non-EU regions), and electricity impacts for non-EU regions are based on IEA scenario analysis of potential future electricity mix to meet different GHG reduction objectives from (IEA, 2017). An illustration of the flow of data through the electricity production module is provided below.

Figure 4.2: Illustration of the potential indicative flow of data through the electricity production module



This module provides aggregated outputs to both the fuels module (3), the final vehicle cycle LCA calculation module (4), and outputs disaggregated by substage[17] to the Results Viewer (module 5). The module can output impact results (per kWh or per MJ of electricity consumed) for average regional generation mixes for different scenarios (discussed further in later Section 4.7.1), as well providing as average results for individual generation types. Key data flows into and out of the module are summarised in Table 4.2.

[17] Impacts split by (i) capital goods (i.e. electricity generation equipment), (ii) production of fuels used in electricity generation, (iii) direct generation emissions, (iv) transmission & distribution losses.

Table 4.2: Key inputs and outputs for Module 2, electricity chains

Key Inputs to Module 2:
• *From Module 1*: Timeseries background LCI datasets relevant to electricity production (e.g. also global and regional average electricity production impacts per kWh electricity consumed)
• *From EC modelling*:
  ○ Electricity generation mix scenario data by scenario, region (2020-2050)
  ○ Other electricity production input data (generation capacity, generation efficiency, net imports/exports, transmission & distribution grid losses, etc) by scenario, region
• *From ifeu Umberto model*: Electricity production emissions/impacts per kWh electricity consumed by generation type (hard coal, lignite, gas, solar PV, etc.), and year (2020, 2030, 2040, 2050)
• *From IEA datasets*: Current and future scenario projections (2015-2060) of generation mix and transmission & distribution losses for China, Korea, Japan, United States and the World.

Key Outputs from Module 2, with timeseries outputs 2020 to 2070:
• *To Module 3*: Electricity chain impacts per MJ electricity consumed by generation type, region
• *To Module 4*:
  ○ Electricity chain impacts per MJ electricity consumed by generation type, region
  ○ Electricity generation mix scenario data by scenario, region
• *To Module 5*: As for Module 4, but with impacts per kWh disaggregated by electricity production stage, i.e. Capital Goods, Fuel production, Generation, Transmission & Distribution Losses.

4.4 Fuel production chain module (3)

Module 3 allows for a well-to-tank (WTT) analysis of 60 different fuel chains, including primary and secondary fossil fuels, primary and secondary biogenic fuels and e-fuels. In addition to the WtT analysis, Module 3 also includes the CO_2 and SO_2 combustion emissions for the various fuels. Biogenic fuel chains are assumed to have zero GHG combustion emissions, while the combustion emissions for the fossil chains are based on the composition of the fuel. All other emissions linked to fuel combustion and other tank-to-wheel (TTW) impacts are assessed in the vehicle's module (Module 4).

The fuels' module includes the lifecycle inventory of the inputs and outputs (and their respective impacts) for each fuel chain. Most background data are imported from Module 1. Foreground data for each fuel chain were assembled from publicly available data, as well as some internal resources. Other key inputs into Module 3 include:

- Electricity production impacts calculated in Module 2 (see Section 4.3).
- Crude oil extraction and refining impacts, as modelled by ifeu's refinery model.
- Agricultural production impacts, which was modelled in Ecoinvent to capture various sources of emissions, e.g. fertilizer use, infrastructure
- iLUC impacts, as modelled by GLOBIOM, including SOC emissions.
- Field N_20 emissions for different biogenic feedstocks from GNOC.

The module provides results by individual fuel chain for each impact category on a per MJ of final fuel basis. Several novel methodological choices were implemented in Module 3, in line with the literature review and stakeholder consultation, including impacts from counterfactual scenarios (consequential LCA) in the case of secondary fossil and biogenic feedstocks, impacts from co-products modelled via substitution and global land-use change (both direct and indirect) impacts of primary biogenic fuels. These methodological choices do not, however, provide sufficiently robust grounds for a like-for-like comparison of fuel chains (See Section 5.3) and consequently of the vehicles using such fuels. In order to improve the robustness and comparability of fuel chains and resulting WTW results, additional methodological choices were built in Module 3 and in the results viewer (See Section 4.6), allowing for co-product allocation to be used instead of substitution and for both counterfactual impacts and land-use change emissions to be removed from the modelling. The resulting set of WTT impacts could therefore be used in Module 4 to allow for a consistent and reliable comparison of powertrains. See Section 5.5.8 for more details.

For fuels where electricity is a key input (e-fuels and hydrogen via electrolysis) two sets of results are calculated, one using only using renewable electricity and one using grid electricity. Blend scenarios have also been included and were determined based on EC modelling. There are 3 gasoline blend scenarios, 3 diesel ones, 3 CNG ones, 3 LNG ones, 2 LPG ones, and 3 gaseous H_2 ones. There are no liquid H2 blends as this is only produced via one fuel chain in Module 3.

Temporal variations across fuel chains are not explicitly modelled, i.e. foreground data does not change with time. Further, all background data, with the exception of electricity from Module 2, also do not change with time. The electricity mix assumes an increasing share of renewables over time, which affects the following:

- The total impacts from fuel production, where electricity is a direct input to the system
- The substitution credit, where electricity is a co-product to the system. As the grid is expected to decarbonise over time, the corresponding GHG emission credit given to co-produced electricity decreases over time.
- The counterfactual impacts, where the feedstock is diverted away from electricity production to fuel production. The corresponding GHG emission burden associated with producing additional electricity decreases, as the average grid intensity decreases.

Key data flows into and out of the module are summarised in Table 4.3

Table 4.3: Key inputs and outputs for Module 3, fuel chains

Key Inputs to Module 3:

- *From Module 1*: Timeseries background LCI datasets relevant to fuel production, including data needed to calculate counterfactual emissions (e.g. for secondary fossil or biogenic fuels).
- *From Module 2*: Electricity chain impacts per MJ electricity consumed by generation type, region
- *From ecoinvent:* Inputs/outputs for several lifecycle stages, e.g. conventional natural gas extraction and processing, CO_2 capture and gas liquefaction, crop cultivation, transport and storage. Modelling of counterfactual uses and substituted products.
- *From GREET:* Inputs/outputs for non-conventional natural gas extraction and processing
- *From JRC/JEC:* Inputs/outputs for several lifecycle stages and fuel chains, e.g. biomass processing, transport and storage.
- *From ifeu refinery model*: Inputs/outputs for oil refining.
- Other fuel production cycle-specific input data/assumptions: i.e. relating to feedstocks and conversion processes, including GLOBIOM results for iLUC, GNOC/IPCC results for fertilisers emissions, average EU SOC losses, and processing stages for synthetic fuels (secondary fossil, secondary biogenic and e-fuels).

Key Outputs from Module 3:

- *To Module 4*:
  - Fuel chain impacts per MJ fuel consumed by fuel chain (total WTT, TTW CO_2/SO_x)
  - Fuel blend scenario impacts per MJ consumed
- *To Module 5*:
  - Fuel impacts per MJ fuel consumed by fuel chain and fuel blend (total WTT, TTW CO_2/SO_x)
  - Fuel impacts disaggregated data by production stage, (a) WTT by: Feedstock, Processing, Transport, LUC, Counterfactual, (b) TTW impacts due to exhaust emissions of CO_2, SO_x
  - Multiple modelling options (i.e. ‘fuel variants’), including energy allocation or substitution for co-product modelling, the possibility to remove counterfactual impacts and the possibility to remove land-use change emissions.

4.5 Vehicle cycle module (4)

This module contains the main vehicle cycle data and calculations, and also brings in (imports) data outputs from the other modules to compile this into the final complete LCA results.

The module was constructed to allow for flexible application of alternative settings for a range of key parameters, to allow for the exploration of uncertainties/sensitivities in these and also for different assumptions linked to specific EC modelling scenario datasets (discussed further in Section 4.7.1). Key sensitivities which can be explored in the module are:

- High-level EU scenario (affecting future electricity mix, impacts from material production, vehicle efficiency improvement): Baseline or Tech1.5 (see later Section 4.7.1)
- Region/country of operation (affecting electricity mix, % share of driving by road type, impacts on LDV average energy consumption due to variation in average ambient temperatures)
- Future material composition of the vehicle glider and mass reduction profile
- Future trajectories in battery performance (energy density, cycle life) and chemistry (affecting vehicle mass, battery impacts)
- Source/type of electricity used in vehicle manufacturing, and battery manufacturing (e.g. grid average vs renewables)
- Vehicle lifetime operational km activity (default / low / high)
- Variation in freight vehicle loading factors (which impacts on running mass, energy consumption and impacts per tkm)
- Variation in end-of-life recycling rates for vehicles and for batteries separately
- Vehicle electric range (default/low/high), which impacts on battery sizing, mass
- Future improvements in regulated exhaust / non-exhaust vehicle pollutant emissions
- Regional share of battery manufacturing (split by cathode materials, cell manufacturing and pack manufacturing)
- PHEV share of electric mileage (to account for operational / behavioural uncertainties)
- Impact on energy consumption due to variation in average ambient temperature
- Variation in xEV battery 2nd life rates / credits

The choice of key sensitivities includes those identified as priorities though consultation with stakeholder experts. The outputs from this final module are exported to a separate readable file that can be imported into the final Results Viewer module (5). Table 4.4 summarises the key data flows in/out of the module.

Table 4.4: Key inputs and outputs for Module 4, vehicle cycle

Key Inputs to Module 4:

- *From Module 1*:
  - Timeseries material and other background LCI data impacts relevant to vehicle cycle
- *From Module 2*:
  - Electricity chain impacts per MJ electricity consumed by generation type, region
- *From Module 3*:
  - Fuel chain impacts per MJ fuel consumed by fuel chain
  - Fuel blend scenario impacts per MJ fuel consumed
- Other vehicle cycle-specific input data/assumptions: vehicle specifications, scaling parameters, lifetime and mileage profiles, component material composition, battery-specific data, etc.

Key Outputs from Module 4:

- *To Module 5*:
  - Combined full vehicle LCA emissions/impact results for specified scenario / sensitivity settings, disaggregated by lifecycle stage (i.e. vehicle production, fuel production/electricity production, vehicle operation, vehicle end-of-life)
  - Additional intermediate results and input data, including: lifetime activity (in vehicle-km or tonne-km), calculated unladen mass and mass including freight loading (tonnes), battery impacts per kWh and energy density (in Wh/kg) projections.

4.6 Results Viewer module (5)

The final results analysis module is a 'Results Viewer', for assessing the final output results files from the detailed vehicle LCA calculations from modules 2-4. Different results output files can be imported into it in a static flat database-style format. The module also contains a range of flexibly configurable summary tables and charts that can be used to explore and interpret results from the analysis.

Table 4.5: Key inputs and outputs for Module 5, results viewer

Key Inputs to Module 5:

- *From Module 4:*
  - Combined full vehicle LCA emissions/impact results for specified scenario / sensitivity settings, disaggregated by lifecycle stage (i.e. vehicle production, fuel production/electricity production, vehicle operation, vehicle end-of-life)
- *From Module 2 and Module 3*:
  - Final average energy carrier emissions/impacts per MJ fuel or kWh electricity used by vehicles in the specified scenario / sensitivity settings.

Key Outputs from Module 5:

- Configurable tables and charts to summarise key results from the vehicle LCA analysis

The flexibility defined in the modelling framework allows for the exploration of a wide range of combinations of data inputs, assumptions and sensitivities, with the theoretical combination of these reaching over a billion rows of data for the overall vehicle LCA alone (as well as many thousands of additional rows of data for the detailed outputs from the fuel and electricity production chain analyses. It was not feasible, reasonable nor necessary to be able to generate and handle this volume of data; in addition, certain outputs were not deemed robust enough to be provided alongside the public report.

A summary of the key (intermediate or overall) output results included in the (publically available) Vehicle LCA Results Viewer provided alongside the report is provided in the following Table 4.6. The following general criteria were therefore used to determine/prioritise the results to be provided (balanced also against the need to keep the provided information to a reasonable/manageable level):

(i) *Importance*: whether the results/information are of particular interest for policy-analysis/making (or other) purposes to the Commission (foremost) and/or the wider stakeholder community.

(ii) *Relevance*: whether the results/information is particularly relevant to meeting the overall objectives for this study, or to aid in interpretation of other/overall outputs, particularly in the context of the two Commission modelling scenarios used as inputs to the future projections.

(iii) *Diversity or representativeness*: whether the provision of information, results or detail are needed to provide a representative picture, or improve the diversity of the results, or add significant additional insights or value to the interpretation of the other project outputs/results.

(iv) *Robustness*: whether the underlying background and foreground data and assumptions, and the application of the methodological approach are deemed to be sufficiently robust to provide a useful comparison with other results, whilst minimising the risk of incorrect conclusions being drawn or potential misuse/misrepresentation of the data.

Table 4.6: Summary of the outputs included and summarised in the Vehicle LCA Results Viewer

Results output	Outputs included in the Vehicle LCA Results Viewer
Electricity production chains	• Results for all generation types and generation mixes, for all impact categories and individual pollutants for all regions covered in the analysis (i.e. EU28 (and individual Member States)
Fuel production chains	• Results are provided for 50 fuel chains* and two fuel blends (for each fuel type), for all LCA impact categories, and individual pollutants, and for three fuel variant results based on alternative methodologies: (i) energy allocation, (ii) energy allocation + counterfactual, and (iii) substitution + counterfactual. Results for primary biogenic biofuels may be also be obtained with or without land-use change emissions.

Results output	Outputs included in the Vehicle LCA Results Viewer
Intermediate vehicle LCA outputs	• A number of intermediate results from the Vehicle LCA model calculations are also provided alongside the overall results to help better add context to these, and to also facilitate conversions between different functional units. These outputs include the following, by vehicle/powertrain type as relevant: (i) total vehicle unladen mass (kg), (ii) vehicle payload (kg), (iii) vehicle lifetime activity (km), (iv) total battery energy capacity (kWh), (v) average battery pack energy density (Wh/kg).
Overall vehicle LCA	• Raw data is output on a utility-basis, which is tkm for lorries, and vkm for all other vehicle categories. Data on lifetime km and tonne-km is also provided to enable conversion between total impact, vkm and tkm units within the tables/charts in the Vehicle LCA Results Viewer (or separately). • Results are provided under the default assumptions/settings for all LCA impact categories and vehicle types, with fuel results (using energy allocation, no counterfactual) based on Baseline and Tech1.5 scenarios. • Additional sensitivity analysis results are provided in separate files for all vehicle types, with various different sensitivity settings – in most cases these are provided for the GWP impact only except for: (a) sensitivities on the improvement in exhaust/TTW pollutant emissions from vehicles, (b) outputs specifically providing impacts of individual pollutant emissions, (c) selected impacts for sensitivities on EU regional variation, and on alternative fuel methodology/data variants.

Notes: Outputs are provided also for both the Baseline and Tech1.5 scenario cases for all datasets. * Output results are excluded for fuel chains based on the following feedstocks, as they were not deemed sufficiently robust: non-conventional crude, municipal solid waste (MSW), and waste industrial gas; results were similarly excluded also for synthetic fuels produced from agricultural residues.

4.7 A summary of key vehicle foreground data/assumptions

This subsection provides a summary of some of the key input assumptions and certain intermediate calculation results that feed into the overall vehicle LCA calculations. This information provides additional context for the overall vehicle LCA results presented in later report sections 5.4 and 5.5.

4.7.1 Summary of high-level scenarios

Outputs from the overall vehicle LCA modelling are provided aligned to specific overall scenario settings applied across all module calculations and a range of variable settings allowing for the exploration of sensitivities. The global/overall scenario settings directly impact in particular the electricity mix used, the future improvement in vehicle technical efficiency and biofuel substitution rates. The vehicle LCA calculations were configured based on data from two alternative modelling scenarios up to 2050, which were used to support the Commission's Long Term Strategy. These are, summarised in Table 4.7 below. Individual settings for a number of key parameters are variable, so they can be set to alternative values to enable the exploration of sensitivities, these are further discussed in later Section 5.5.

The modelling datasets aligned to the two scenarios that have been used in the analysis include the following elements:

1) *Transport input data by vehicle type:*
    a) % improvement in real-world MJ/km 2020-2050 by vehicle/powertrain type
    b) % share urban / non-urban driving by vehicle type (average across time series)
2) *Electricity input data for EU28, individual countries:*
    a) Electricity generation mix 2020-2050
    b) Generation efficiency by generation type, 2020-2050
    c) Transmission & distribution losses
    d) Net imports/exports from individual countries to the wider EU.
3) *Fuels:* % substitution rate of conventional fossil fuels with biofuel/low carbon fuels from 2020-2050, by fuel type.

Table 4.7: Summary of vehicle LCA modelling scenarios

Scenario	Description
Baseline	Baseline scenario including all currently planned/ implemented EU and national policies.
TECH1.5	Scenario consistent with the EU contribution to meeting the Paris Agreement objective of keeping global temperature increase to a maximum of 1.5 °C*.

Notes: * Long-Term Strategy to reach a climate-neutral Europe by 2050; ** EC PRIMES / PRIMES-TREMOVE model outputs for EU28, supplemented by similar IEA ETP 2017 datasets for non-EU regions for electricity mix.

4.7.2 Assumptions for a selection of key vehicle parameters

The following tables and charts provide a high-level summary of some of the key assumptions used in the calculations of impacts in the LCA modelling, including the following by vehicle type:

- A summary of the key reference vehicle/powertrain input parameters (Table 4.8).
- Lifetime activity (in km) and vehicle life (years) (Figure 4.3).
- Default electric range assumptions for BEV and PHEV powertrains (Figure 4.4).
- Calculated BEV battery capacity (in kWh) (Figure 4.5).
- Utility Factor (UF) for PHEV electric range calculations for LDVs (Figure 4.6). (For HDVs, the electric km share is calculated from the average working day km[18] and the electric range).
- Assumptions on the share of xEV battery repurposing for second life (Figure 4.7).
- Examples of the material composition and mass for the lower medium car glider and complete reference vehicle (Figure 4.8).

The assumptions for the average reference powertrain parameters for light duty vehicles (cars and vans) were calculated based registrations-weighted averages from the 2018 car and van CO_2 monitoring databases (EEA, 2019) (EEA, 2019a), with energy consumption extrapolated to an estimated 2020 vehicle. For heavy duty vehicles, the energy consumption per km was based on VECTO[19] simulation results for the generic vehicle types included in the model at 50% loading on the respective reference cycle for the rigid lorry, the urban bus and coach. For the articulated lorry, fuel consumption is based on ~36 litres/100km for a Class 10 (tractor-trailer) lorry from JRC/OEM VECTO simulation data in (JRC, 2018). The other reference vehicle/powertrain specifications were taken from the generic VECTO model specifications and (Ricardo Energy & Environment et al., 2015). The draft assumptions for reference powertrain vehicle mass, energy consumption and power were sent to expert stakeholders including OEMs, supplies and their European associations for feedback during the data validation exercise, and amendments made based on any comments received. Further information on this exercise is provided in Appendix A2 of this report.

For light duty vehicles, the default lifetime km assumptions by vehicle segment were based on assumptions (CE Delft et al., 2017), which are based on recent detailed analysis for the Commission on the real-world LDV lifetime mileage by (Ricardo-AEA, 2014a), and from analysis of second-hand vehicles by (TML et al, 2016). The high/low sensitivities for LDVs are indicative assumptions based in part on a range of values typically used in the literature. For heavy duty vehicles, the vehicle life and lifetime mileage are based on our previous analysis for the Commission for the relevant vehicle categories/duty cycles (Ricardo Energy & Environment et al., 2015) and +/- 20% for the sensitivities.

Study assumptions for electric range based on a market analysis by Ricardo for available and proposed models (e.g. for heavy duty vehicles, where certain powertrains are not yet available in all categories), and future expectations based on mass deployment and battery technology improvements and cost reduction. These assumptions were also included/checked in the data validation exercise.

Further detail on other key input assumptions and data is also provided in Appendix A4 of this report.

[18] Average working day km is assumed to be = Lifetime km / Life (years) / 250

[19] VECTO is the new simulation tool that has been developed by the European Commission and shall be used for determining CO_2 emissions and Fuel Consumption from Heavy Duty Vehicles (trucks, buses and coaches) with a Gross Vehicle Weight above 3500kg. (European Commission, 2020a)

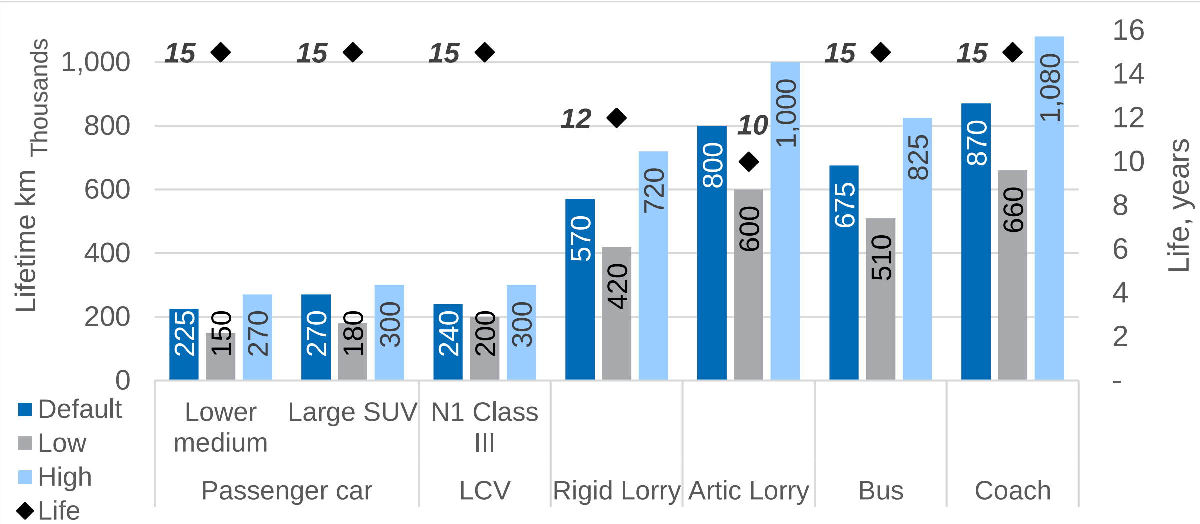
Table 4.8: Reference vehicle and powertrain characteristics used in the analysis

Vehicle Type	Powertrain Reference	Cycle	Energy, MJ/km	Mass, kg	GVW, kg	Power, kW	Average Load, %	Capacity, kg
Car Lower Medium	ICEV-G	WLTP	2.17	1,325	3,500	96	N/A	N/A
Car Large SUV	ICEV-D	WLTP	3.06	2,125	3,500	182	N/A	N/A
Van N1 Class III	ICEV-D	WLTP	2.72	2,217	3,500	106	30%	1,208
Rigid Lorry 12t GVW Box	ICEV-D	Urban Delivery	10.10	6,130	12,000	175	40%	5,795
Artic Lorry 40t GVW Box	ICEV-D	Long Haul	12.95	14,377	40,000	325	40%	25,548
Bus 12m Single Deck (SD)	ICEV-D	Urban Bus	12.60	12,008	18,000	175	20%	5,917
Coach 24t GVW SD	ICEV-D	Coach	9.36	13,335	24,000	350	30%	10,590

Source: Based on market average data for LDVs (cars and vans), and default values/results from VECTO simulation of generic vehicle types for HDVs; further detail on sources is provided in Appendix A4.

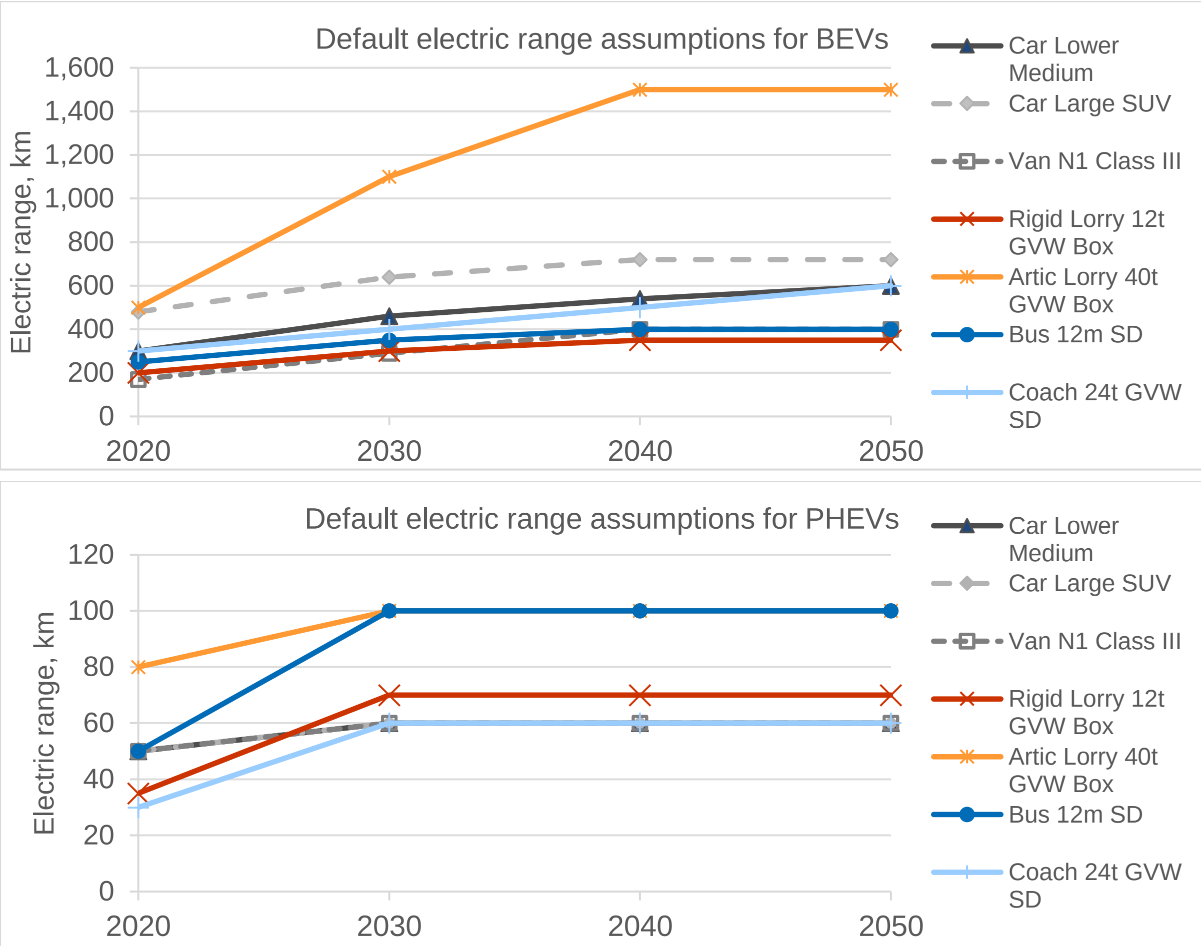
Notes: Energy consumption, vehicle unladen mass and total payload capacity are calculated within the LCA model for the other different powertrain types. Mass and capacity parameters are calculated based on the scaling parameters for different system components and other factors, such as the electric range (which affects the size/mass of the required battery).

Figure 4.3: Summary of the default assumptions on lifetime kilometre activity and life in years



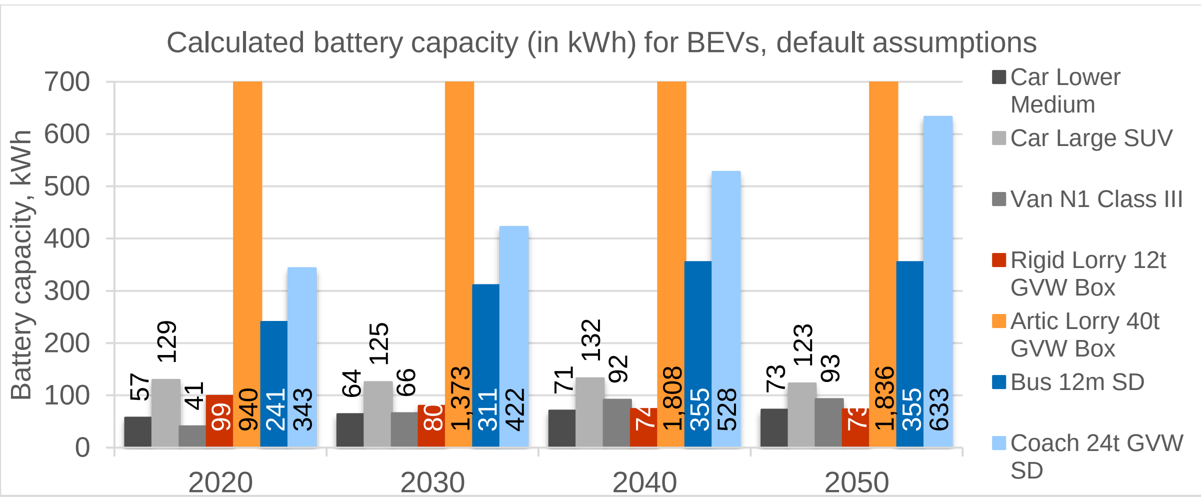
Source: Default assumptions based on (CE Delft et al., 2017) and (Ricardo Energy & Environment et al., 2015).

Figure 4.4: BEV and PHEV electric range default assumptions by vehicle type



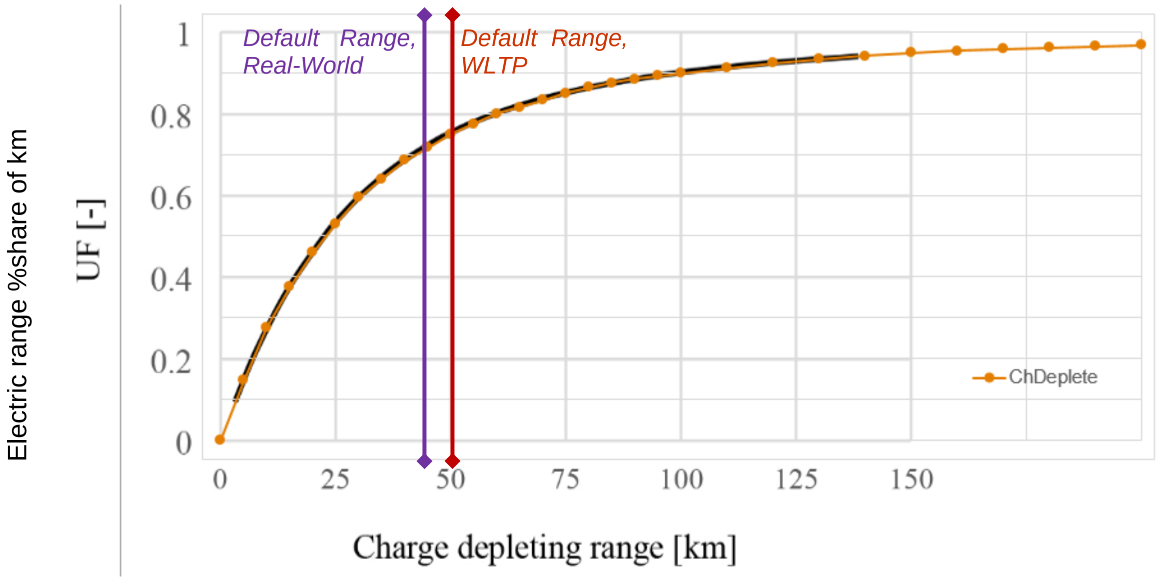
Notes: Electric range defined based on standard test cycle, which is WLTP for LDVs. For HDVs the following base VECTO cycles are assumed: Rigid = Urban Delivery, Artic = Long haul, Bus = City urban bus, Coach = Coach. Study assumptions for electric range based on a market analysis by Ricardo for available and proposed models, and future expectations based on mass deployment and battery technology improvements and cost reduction.

Figure 4.5: BEV battery capacities by vehicle type, calculated based on the study methodology using default electric range and baseline vehicle energy consumption projections



Notes: Future battery capacities are lower in the Tech1.5 scenario as this assumes greater future improvements in overall vehicle efficiency, therefore requiring smaller batteries to achieve the same overall electric range.

Figure 4.6: WLTP LDV utility function – default assumptions for PHEVs



Notes: UF is defined according to Commission Regulation (EU) 2017/1151, Sub-Annex 8, Appendix 5.

Figure 4.7: Assumed shares of battery repurposing for second-life

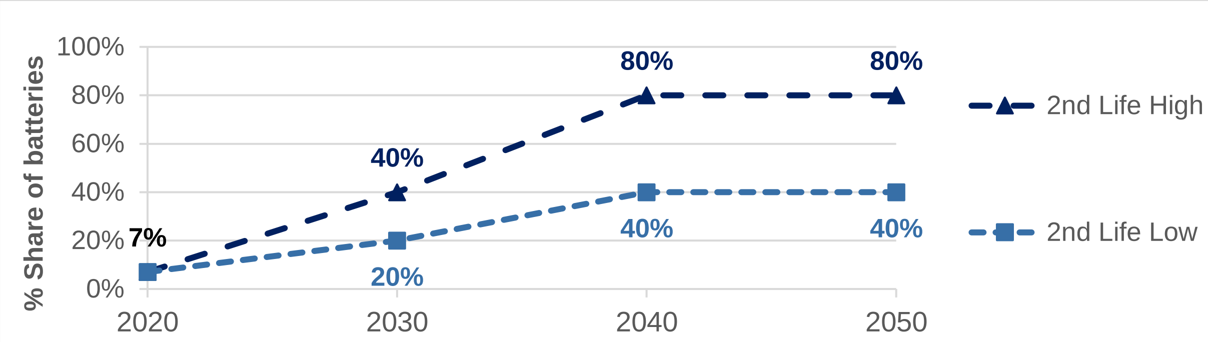
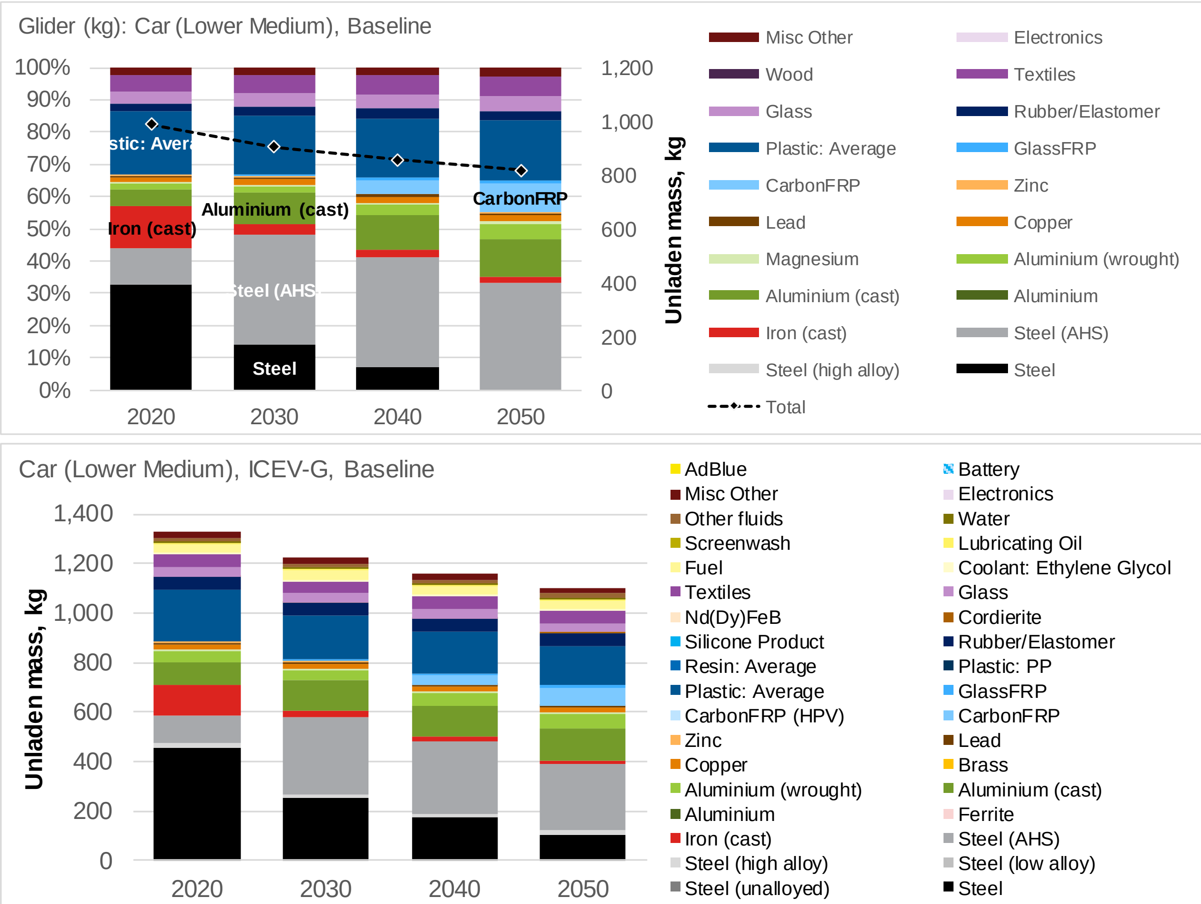


Figure 4.8: Current and projected future material glider composition and complete reference powertrain material composition for the Lower Medium Car, Baseline scenario



4.7.3 Battery characterisation and intermediate results for battery manufacturing

Figure 4.9 provides a summary of key input assumptions and the intermediate results for the battery manufacturing calculations. These include:

a) The input market average technology mix assumptions for vehicle traction batteries. The 2020 shares are based on Ricardo's previous research on the current market mix (Ricardo Energy & Environment, 2019); future projections were developed based on discussions with Ricardo's battery technology experts in our engineering divisions. Draft assumptions were also shared with key expert stakeholders during the project's data validation exercise:

   (i) The average market mix assumed for different NMC cathode technologies for batteries with NMC Li-ion chemistries (the numbers represent the relative % shares of Nickel : Manganese : Cobalt in the cathode).

   (ii) The average market mix of different battery chemistries used in the calculations.

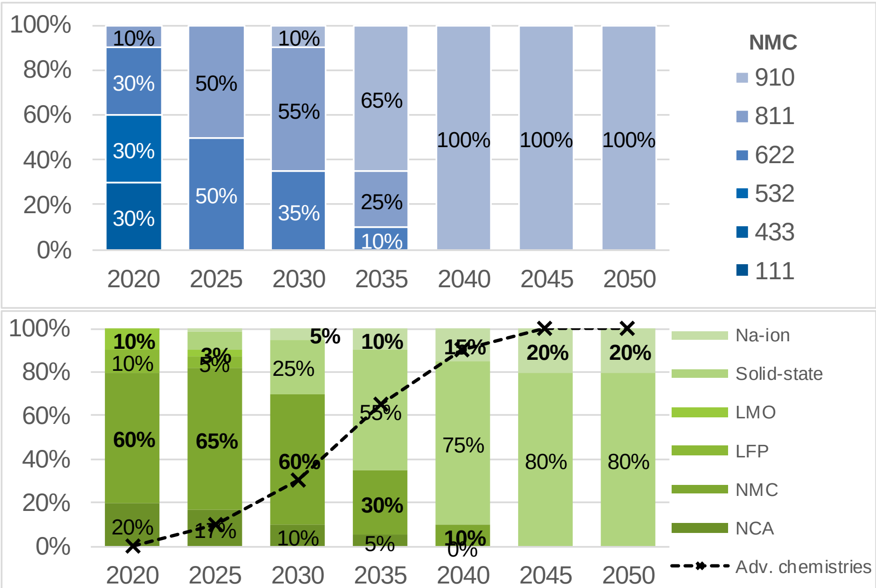
b) The input assumptions on the current and projected future improvement in battery pack energy density (in Wh/kg): these are based on a combination of the default (2020) energy densities for different battery chemistries – mostly based on (ANL, 2018), as well as assumed global overall improvements in projected battery energy density based on Ricardo's view on the technical potential in this area. Three alternative scenarios are presented for these.

c) Intermediate outputs from the battery module calculations for the GWP impact category: Share of GWP impacts for the average traction battery (based on the market mix of technologies) for different battery cell/pack components, and the time series trend in this.

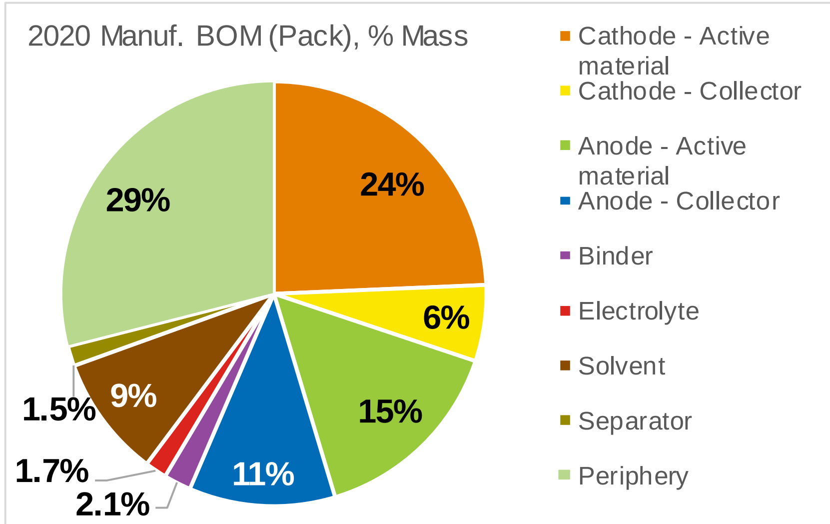
Further information is also provided in Appendix A4 on the assumptions for traction batteries.

Figure 4.9: Summary of key assumptions for battery-related calculations in the LCA modelling, and intermediate outputs

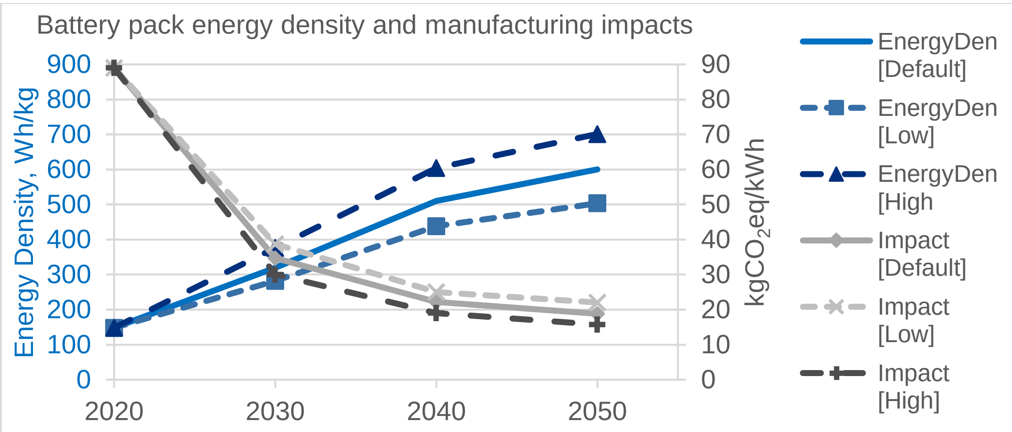
(a) Default battery technology mix assumptions (i) NMC cathode type, (ii) chemistry



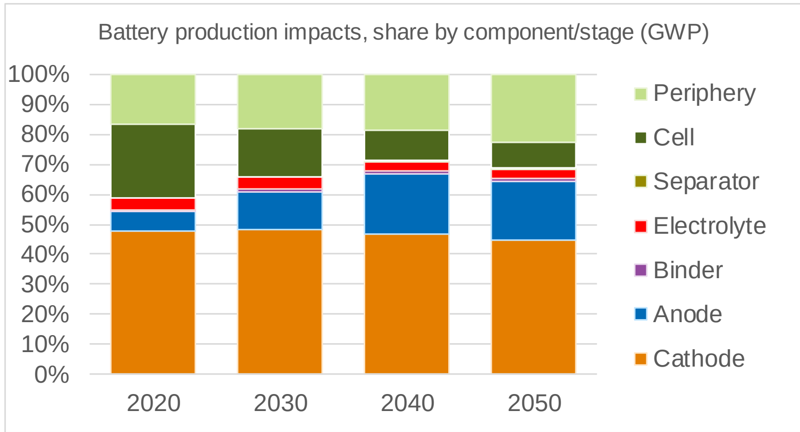
(c) Intermediate battery manufacturing calculation results (GWP):



(b) Input assumptions for battery pack energy density and output GWP impacts



(d) Intermediate battery manufacturing calculation results (timeseries)



Notes: For the intermediate battery manufacturing calculation results, 'Cell' = the impacts from manufacturing energy consumption, and 'Electrolyte' includes also the solvent.

4.7.4 Key input assumptions on electricity generation mix and fuel blends

4.7.4.1 Electricity generation mix

Figure 4.10 provides a summary of the average electricity generation mix used in the overall Vehicle LCA modelling for the two scenarios, as a percentage of the total generation mix. The figure also provides a summary of the output GWP impacts resulting from the defined generation mix assumptions, and the impacts of individual generation types calculated in the modelling. The blend/mix of electricity production chains assumed are taken directly from the relevant EC modelling scenarios (as outlined in Section 4.7.1).

Further information on the results for individual generation types, and the breakdown into different stages for electricity generation are provided in Section 5.2.

4.7.4.2 Fuel blends

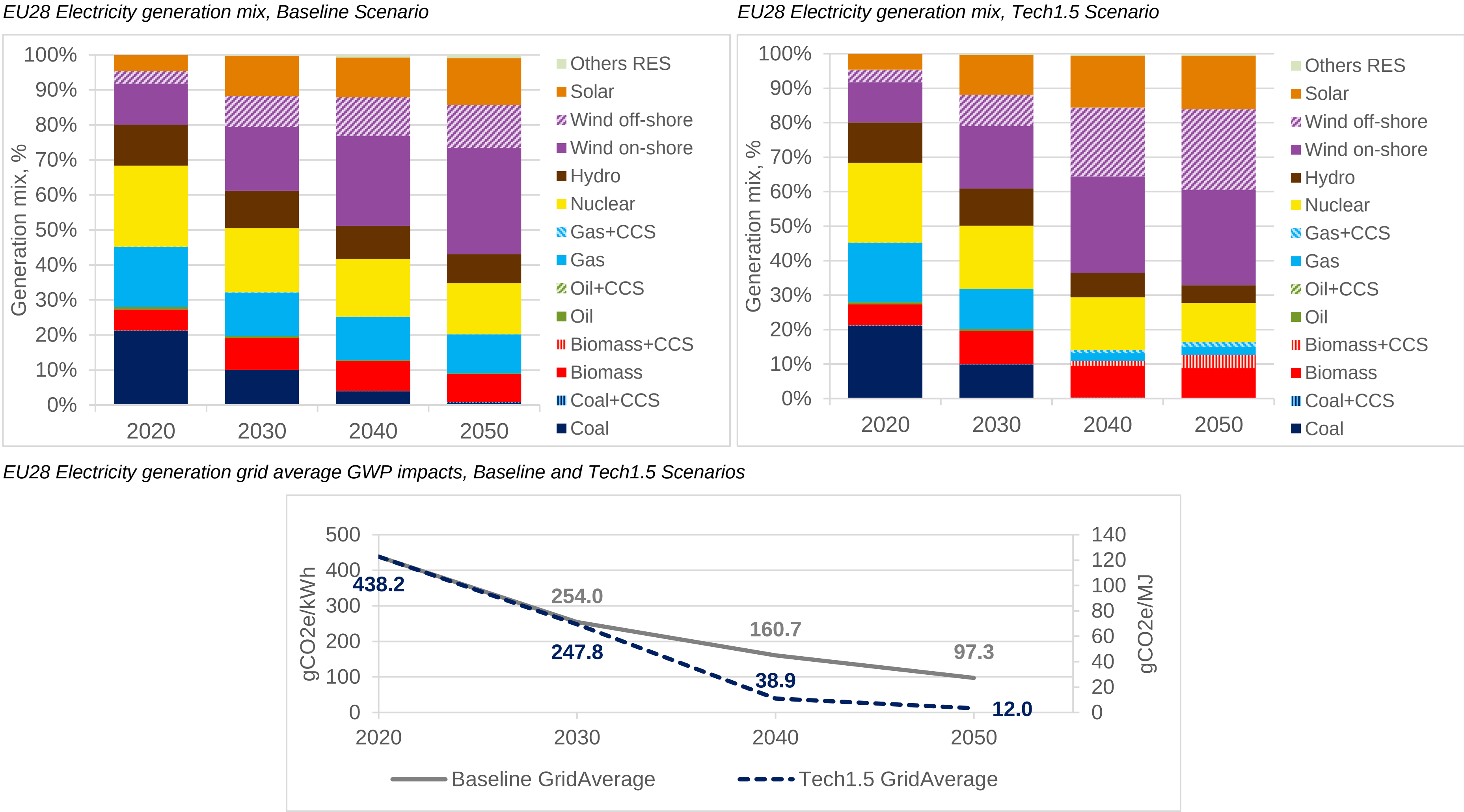
Figure 4.11 provides a summary of the average mix of fuel production chains assumed for the general overall vehicle LCA comparative analysis of impacts. The future shares of different low carbon fuel production chain types have been estimated by the study team to represent what might be anticipated in the two scenarios. However, it should be noted that these blends are only indicative as they were limited by the subset of the currently available fuel production chains that have been modelled as part of this project (e.g. no bio-LPG fuel chains have been modelled in this study, so 100% fossil LPG is included across the timeseries). The following general principles have been used to define the blends:

- These blends have been defined to be consistent with the total share of substitution of conventional fossil fuels for the relevant EC modelling scenarios (as outlined in Section 4.7.1).
- By default, the fuel chain results included in the blends used in the overall vehicle LCA are derived based on the energy allocation methodology and *without* the counterfactuals (i.e. effectively an attributional approach), because:
  a) This provides a more internally consistent methodological basis across all the different modelled fuel chains (and also the wider vehicle cycle LCA modelling);
  b) Some of the available datasets and assumptions used for the more novel consequential and substitution methodological modelling were less robust.
  c) This methodological basis aligns more closely with existing regulatory norms, better aiding comparisons also with other studies.
- Fuel chains where the results have been deemed to be not sufficiently robust (e.g. based on the quality of the available input data) have not been included in the blends (see Appendix A4 for further information).
- The 2020 mix of biofuels is estimated based on the current reported mix of feedstocks/processing; it is assumed that by default this capacity/share is maintained going forwards, with any increase in share in the future being met predominantly by new low carbon feedstocks/processes.
- It is assumed that the future mix of low carbon fuels will be influenced by the following factors: (i) maturity/deployment of production processes, (ii) priority given to lower carbon feedstocks/ production chains – i.e. particularly avoiding those with significant LUC impacts, (iii) potential future resource availability / resource efficiency.

Figure 4.12 provides a corresponding summary of the GWP impacts resulting from the defined fuel blend/production mix assumptions – i.e. the assumed market average % share of different non-conventional/non-fossil fuels used in vehicles (or in the case of hydrogen, the share production chains).

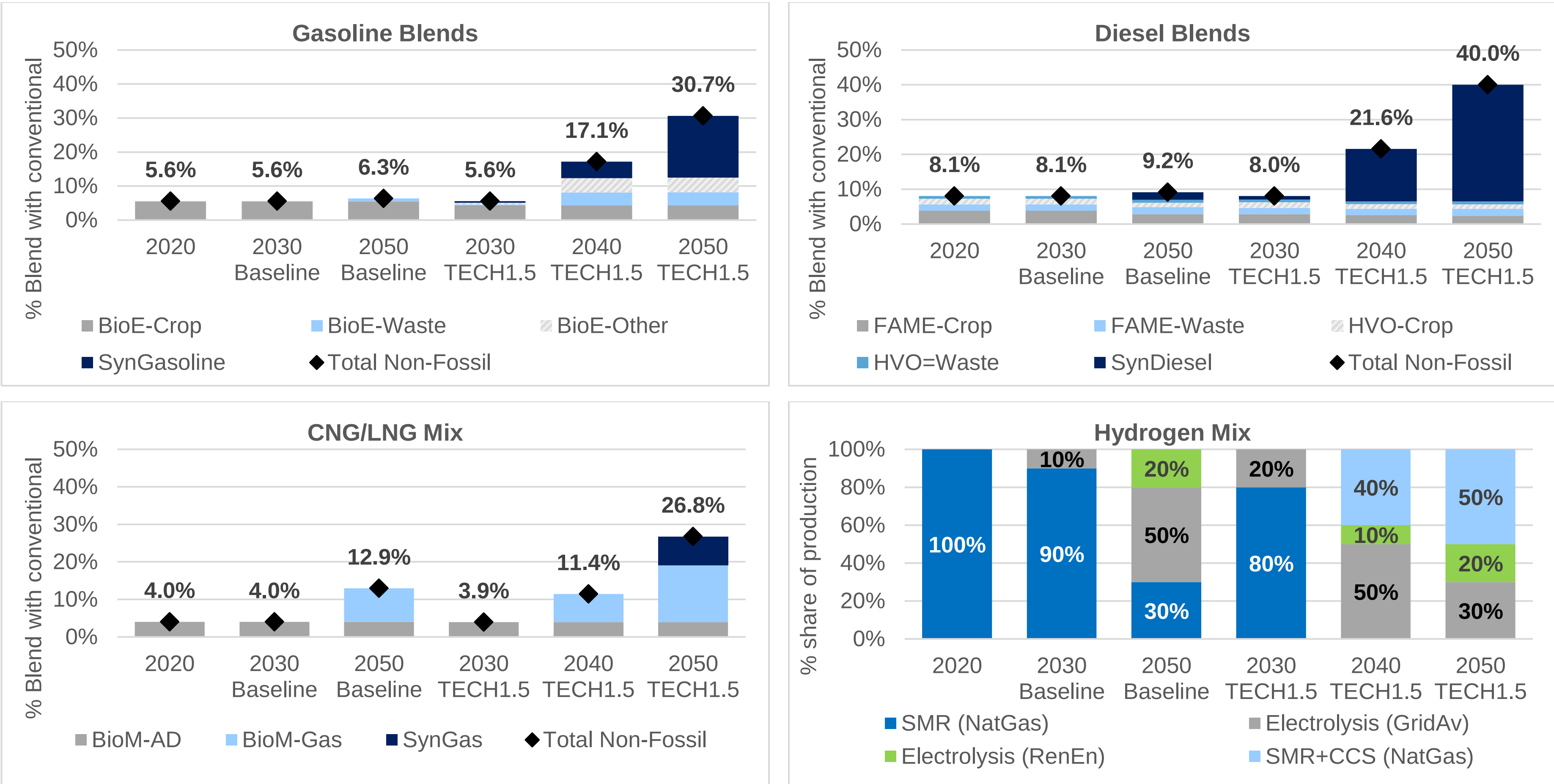
Further information on the results for individual fuel chains is provided in Section 5.3.

Figure 4.10: EU average electricity generation mix assumptions used in the overall Vehicle LCA modelling, as a percentage of the total generation mix



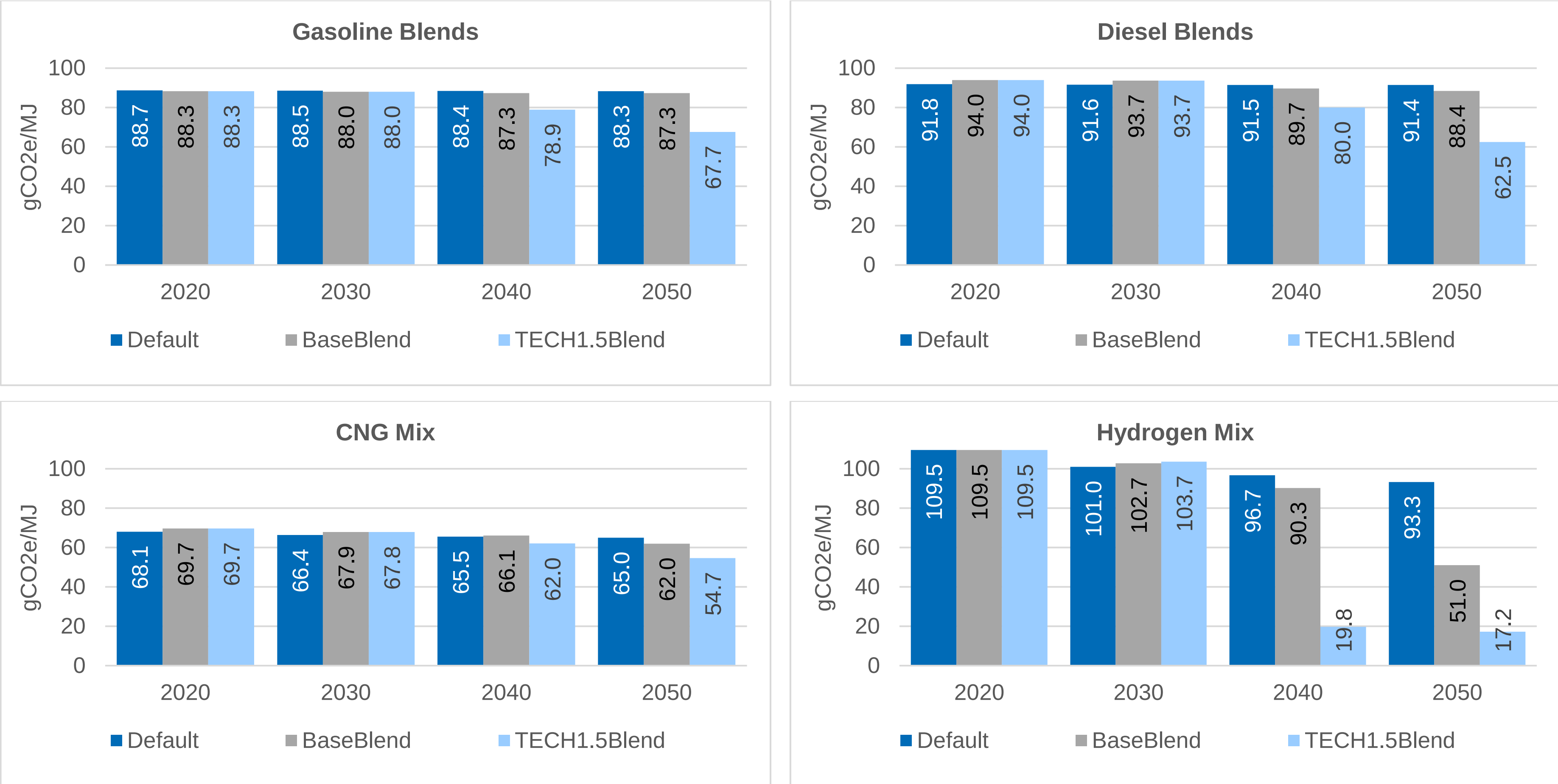
Notes: The blend/mix of electricity production chains assumed are taken directly from the relevant EC modelling scenarios – i.e. the baseline scenario and TECH1.5 scenario, with the net GWP impacts being calculated via the relevant electricity model for this project.

Figure 4.11: EU fuel blend/production mix assumptions used in the overall Vehicle LCA modelling, as a percentage of the total including conventional fossil fuels



Notes: The blend/mix of fuel production chains assumed are only indicative as these were limited by the subset of the currently available fuels that have been modelled as part of this project. BioE = bioethanol, BioM-AD = biomethane from anaerobic digestion process chains, BioM-Gas = biomethane from gasification process chains, SynGasoline / SynDiesel includes e-fuel / PtX chains as well as biomass-to-liquid (BtL) chains.

Figure 4.12: Summary of GWP impacts resulting from the EU average fuel blend/production mix assumptions used in the overall Vehicle LCA modelling



Notes: The blend/mix of fuel production chains assumed are only indicative as these were limited by the subset of the currently available fuels that have been modelled as part of this project. Default values are for 100% fossil diesel, gasoline or natural gas and in the case of hydrogen SMR reforming of natural gas; BaseBlend is the blend assumed under the baseline scenario and TECH1.5 scenario the blend assumed under the TECH1.5 Scenario.

5 Discussion of the results from the application of the LCA methodology

5.1 Introduction

The application of the developed LCA methodology for this study, when using specific modelling choices for fuel chains (energy allocation, no counterfactual) has enabled a harmonised comparison of the environmental performance of selected vehicle categories over all stages of the vehicle life-cycle. It has allowed examining the consequences of methodological choices and key assumptions used in LCA on the calculated environmental impacts. It has led to the identification of potential hotspots, areas of uncertainty and areas for potential future improvement.

Every attempt was made to ensure that data used in the study was as robust as possible, but given the breadth of the study and the quantity of foreground data required, there are some areas, where data is less robust. This is particularly the case for some of the fuel chains where the production process is not yet fully demonstrated and data in the literature is limited and often inconsistent, and the resources available for the study did not permit primary research to strengthen this data.

The study cannot therefore be considered to provide definitive, absolute results on the environmental impacts of vehicles. However it provides a strong and robust indication on the relative performance of the different options (using the most current datasets available), particularly for vehicle powertrain comparisons, electricity chains and for certain categories of fuels, for which results are considered sufficiently reliable. Furthermore it provides a good indication of how different situations and potential future developments may affect these comparisons.

The study also provides key analysis and conclusions regarding the use of novel methodological approaches, such as the use of multifactor substitution and counterfactual scenarios in fuel chains, or the modelling of different electricity production scenarios.

A selection of key results from this analysis are presented in the following report sections. These results are necessarily a subset of the complete analysis dataset, which is far too extensive to present here, but is made available alongside this final report and will be explorable using the developed 'Results Viewer'. Further information is also presented in Appendix A5 of this report.

Because of their overall significance in the complete vehicle LCA, due to the predominance of impacts resulting from the operational phase, a detailed summary is provided on the results from the calculation of impacts from electricity production (in Section 5.2), and from fuel production (in Section 5.3). The main results of the complete LCA including all three vehicle lifecycle stages (production, operation and end-of-life) are presented in Section 5.4.

Finally, a comprehensive assessment of the influence on the overall result of assumptions and uncertainties for key vehicle parmeters is provided in Section 5.5, which have been identified in the review of literature, and also prioritised/requested for inclusion by the expert stakeholders consulted during the project. This final setion is of particular importance as it also helps to disprove commonly propogated myths regarding the significance of key assumptions on the benefits of alternative powertrains, as well as providing valuable insights into potential areas for improvement or policy action.

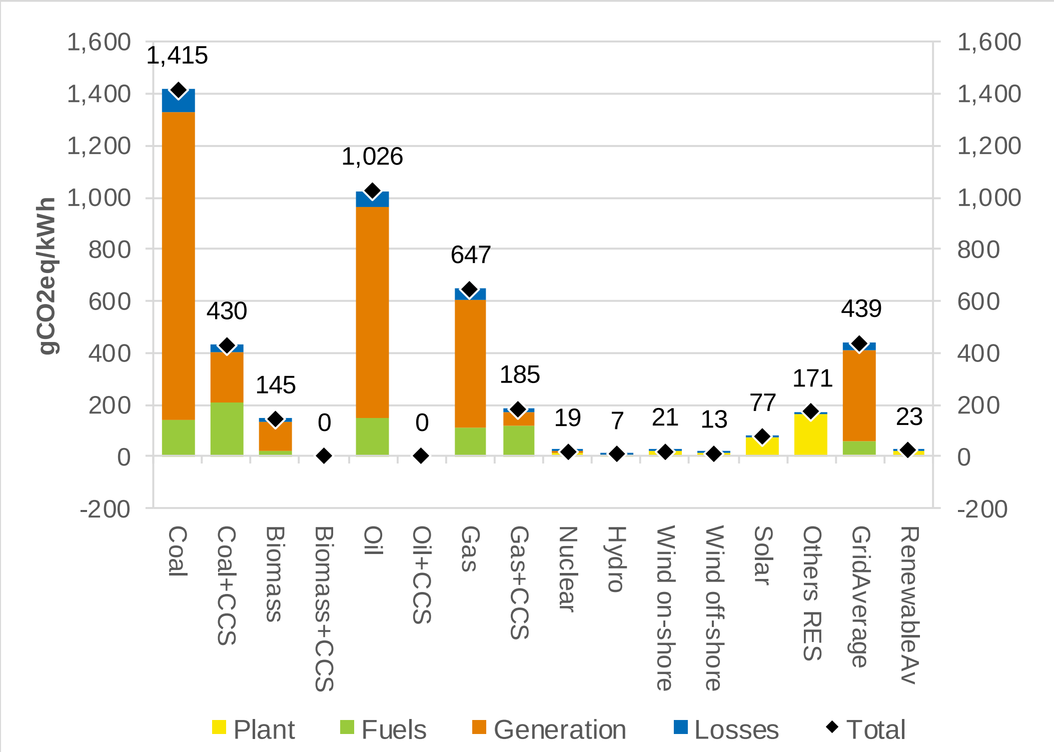
5.2 Results for electricity production chains

This section presents the LCA results for the production and provision of electricity. Results presented here are for the average European electricity mix; results for individual Member States are available in the MS Excel datasets and 'Vehicle LCA Results Viewer' that accompany this report.

As described in Section 3.3, a wide range of both fossil fuelled generation types (with or without carbon capture and storage (CCS)) and renewable energy systems (RES) were modelled, and the differing characteristics of these technologies mean that results of the LCA vary greatly.

In general, fossil fuelled electricity chains have significantly greater environmental impacts across the board, compared to RES or nuclear power generation. This is especially apparent in the GWP impact category, as illustrated in Figure 5.1. This also shows that application of CCS to fossil fuelled generation plants reduces their GWP impact substantially, but it is still higher than that of nuclear and renewable technologies. Moreover, as application of CCS reduces the net generating efficiency of the power plants, it increases all other investigated impacts. The following Figure 5.1 illustrates the total impacts for each generation technology as such (Total, Well-To-Tank, in this case referring to all lifecycle stages of electricity production starting with the production of raw materials to the provision of electricity to the vehicle battery ("tank")), Furthermore, the respective contributions of relevant sub-stages, e.g. the production of fuels used to generate electricity (Fuels) or the impacts associated with transmission and distribution (Losses) are illustrated with their relative share for each technology.

Figure 5.1: GWP of different electricity generation technologies in the EU28, Baseline scenario 2020

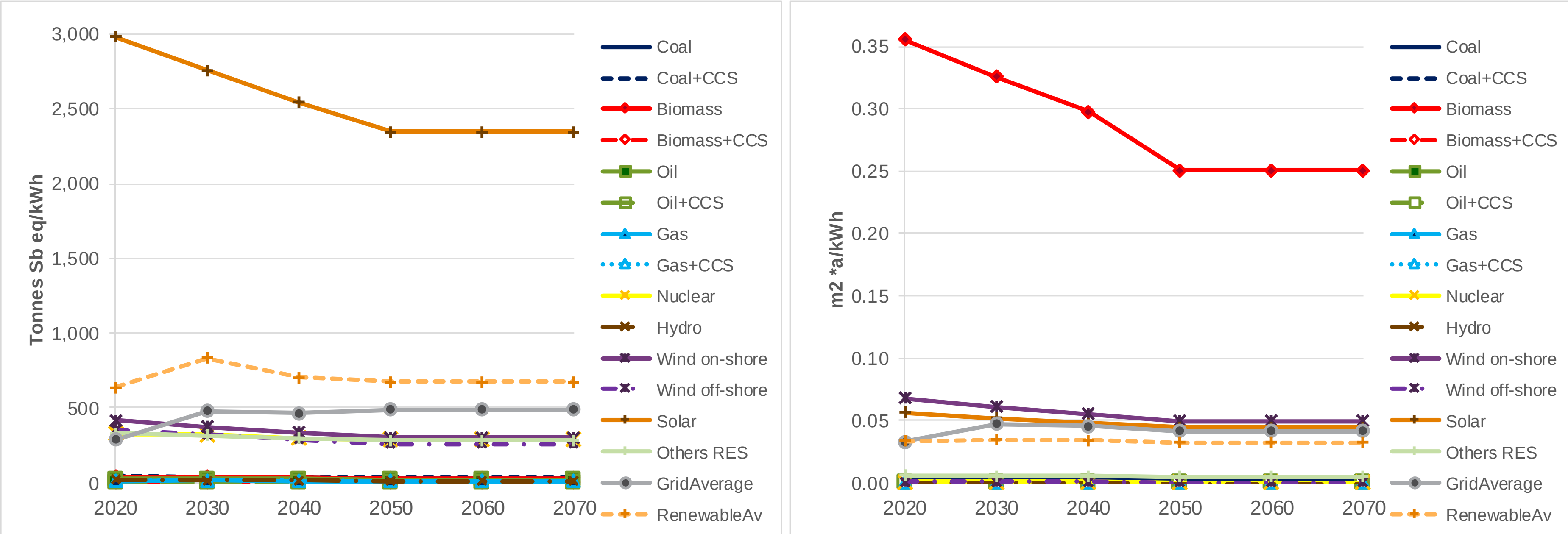


Notes: Plant = Capital Goods: Provision of Infrastrucutre; Fuels = Electricity Fuels: Provision of fuels to generate electricity (e.g. coal, gas, biomass, etc.); Generation: Emissions related to the power plant process itself, meaning direct emissions from the power plant (e.g. exhaust fuems of a coal-fired power plant); Losses = Transmission and Distribution: The emissions derived from efficiency losses due to transmission (regional, international) and distribution (local) of electricity; Total: The sum of all stages. 'RenewableAv' generation includes only intermittent renewable generation (i.e. excludes biomass generation technologies).

Results for other impact categories show a similar trend with high impacts for fossil options, low impacts for RES, especially wind and hydro powered plants. The only impact categories where RES performed worse on average than fossil electricity generation are Abiotic Resource Depletion (where the impacts for Solar PV is an order of magnitude higher than most other gernation types) and Land Use – as illustrated in the following Figure 5.2.

Figure 5.2: Timeseries of (i) ARD_MM and (ii) LandU impacts of different electricity generation technologies in the EU 28, Baseline scenario

(i) Impacts for Abiotic Resource Depletion, minerals and metals (ARD_MM) *(ii) Impacts for Land Use (LandU)*



With respect to Abiotic Resource Depletion, the higher impacts for RES (shown in Figure 5.2) are due to the fact that, when compared to fossil generation, these on average utilise a higher share of metals (e.g. silicon within a PV module) per kWh_{el} produced. Concerning Land Use impacts, the higher impacts are due to the fact that fossil power plant infrastructure is highly centralised, and the utilised fuels are - for the most part - produced in underground mining[20]. RES utilise a comparatively decentralised infrastructure and smaller individual power plants[21]. In addition, especially biomass from primary sources[22] cover large areas for the cultivation of plants, hence the relatively greater impacts for RES.

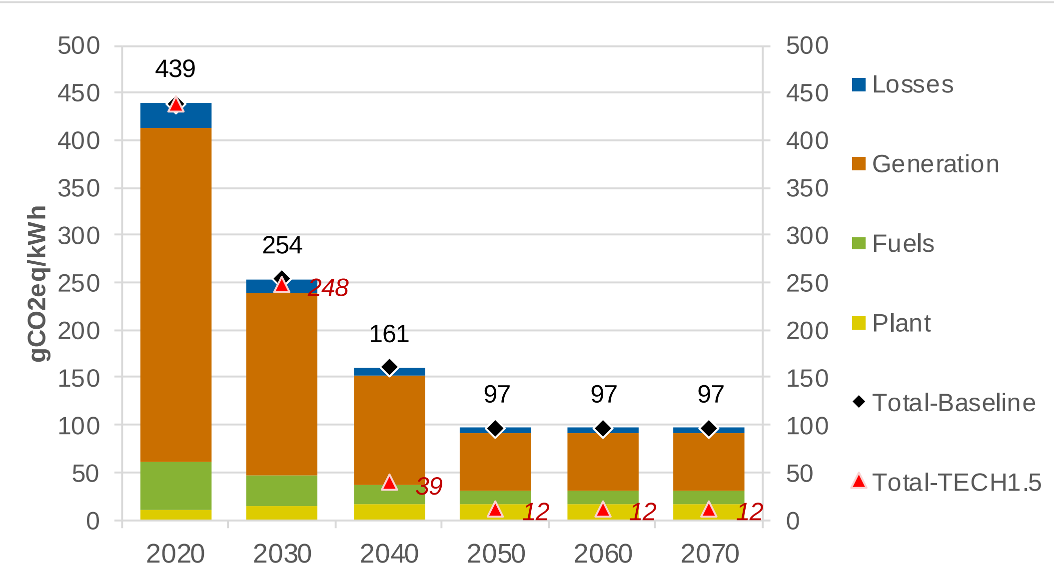
The contribution of different lifecycle stages to the overall impact also differs considerably between generation types. Whereas for fossil-fuelled power generation, the greatest contribution comes from the generation stage (Generation in Figure 5.1), the largest contribution for renewables (except biomass) comes from the manufacturing of the infrastructure (e.g. a photovoltaic module or a wind turbine).

5.2.1 Results for the EU average electricity production

The two scenarios, Baseline and TECH1.5, which are based on EC PRIMES modelling differ mainly in terms of the composition of the electricity mix and the generation efficiencies assumed for technologies. Earlier Figure 4.10 in Section 4.7.4, provided an overview of the composition of the electricity mix from 2020 to 2050 for the two scenarios.

In both scenarios, there is a shift from conventional fossil fuel power generation toward renewables, but the degree and tempo of the change is greater in the TECH 1.5 scenario. Moreover, CCS options especially for biomass fuelled power plants are envisioned in the TECH 1.5 scenario, but not in the Baseline scenario. This shift in the composition of the power mix results in significant changes in impacts, most noticeably, in the impact category GWP. This falls from about 440g CO_2eq/kWh in 2020 to 97g CO_2eq/kWh in the Baseline scenario in 2050 and 12g CO_2eq/kWh in the TECH 1.5 scenario (see Figure 5.3 and Figure 5.4 respectively).

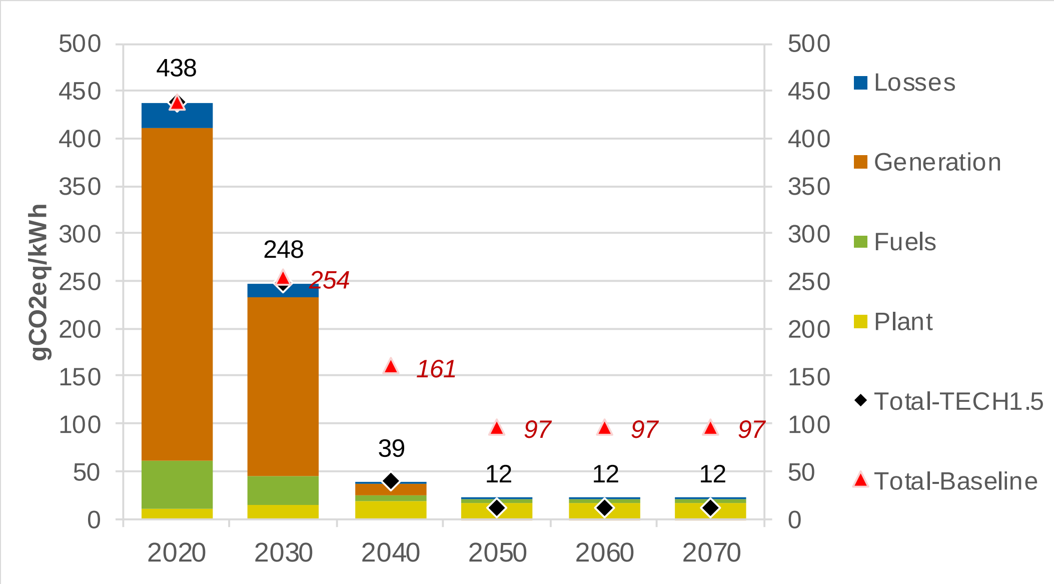
Figure 5.3: GWP of the EU28 average electricity mix in the Baseline scenario, by stage



Notes: Plant = Capital Goods: Provision of Infrastrucutre; Fuels = Electricity Fuels: Provision of fuels to generate electricity (e.g. coal, gas, biomass, etc.); Generation: Emissions related to the power plant process itself, meaning direct emissions from the power plant (e.g. exhaust fuems of a coal-fired power plant); Losses = Transmission and Distribution: The emissions derived from efficiency losses due to transmission (regional, international) and distribution (local) of electricity; Total: The sum of all stages.

[20] Lignite, especially in the EU, is an exemption as it is produced in open-pit mining.
[21] A state-of-the-art wind turbine e.g. has a capacity of 4.5 MW whereas an exemplary modern coal power plant comprises of several lines with a capacity of 500+ MW each.
[22] Referring to typical biomass products such as maize in distinction to secondary feedstock's such as wastes of biogenic origins.

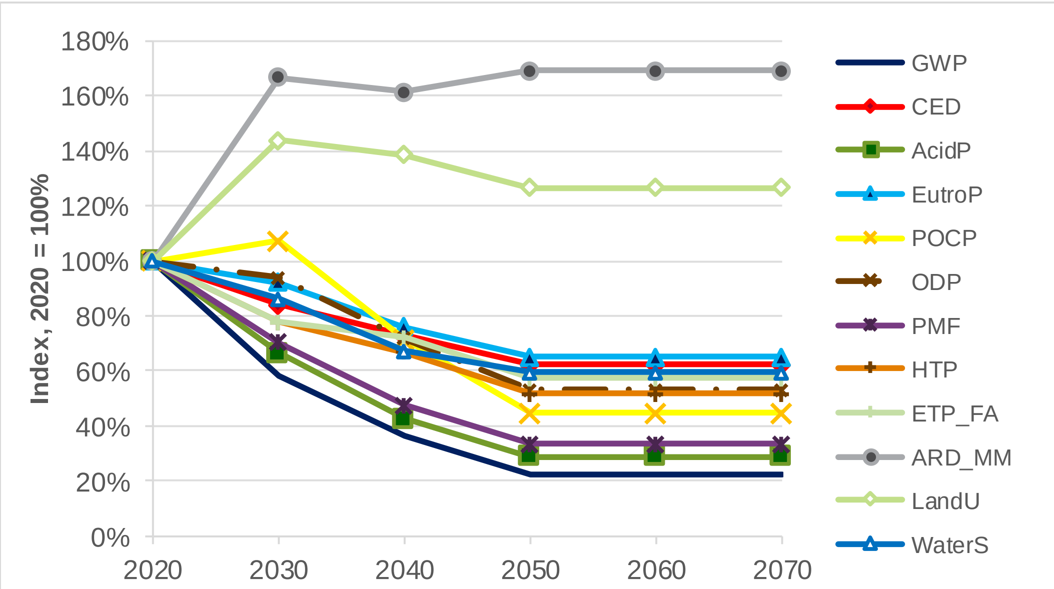
Figure 5.4: GWP of the EU 28 average electricity mix, TECH 1.5 scenario



Notes: Plant = Capital Goods: Provision of Infrastrucutre; Fuels = Electricity Fuels: Provision of fuels to generate electricity (e.g. coal, gas, biomass, etc.); Generation: Emissions related to the power plant process itself, meaning direct emissions from the power plant (e.g. exhaust fuems of a coal-fired power plant); Losses = Transmission and Distribution: The emissions derived from efficiency losses due to transmission (regional, international) and distribution (local) of electricity; Total: The sum of all stages.

A similar trend of impacts reducing over time due to the change in generation composition is seen for most other impact categories (Figure 5.5). Only the impact categories Land Use (LandU) and Abiotic Resource Depletion (ADR_MM) increase over time and are respectively 70% and 23% higher in 2070 than in 2020, which is due to significant increase in the shares of renewables that have high impacts in these categories (as illustrated in earlier Figure 5.2). Figure 5.5 shows results for the Baseline scenario, and the same trajectory is observed for all impact categories in the TECH 1.5 scenario but to a greater degree and rate of change, due to the more progressive change towards low carbon generation.

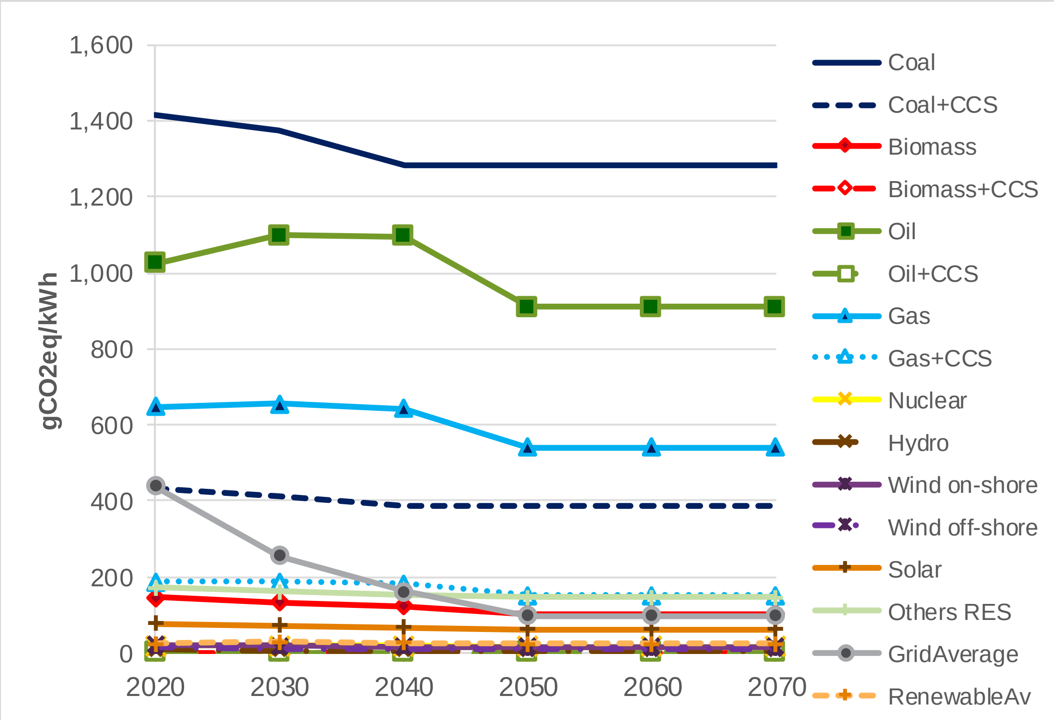
Figure 5.5: Development of impacts of the EU28 average power generation, Baseline scenario



Notes: GWP = Global Warming Potential, CED = Cumulative Energy Demand, AcidP = Acidifying Potential, EutroP = Eutrophication Potential, POCP = Photochemical Ozone Creation Potential, ODP = Ozone Depletion Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ETP_FA = Freshwater Aquatic Eco-Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, LandU = Land Use, WaterS = Water Scarcity

While the main driver of the downward trend in impacts is the changes in the generation mix, there is also a small contribution from technological advances in individual power generation technologies (based on the input data from EC modelling on the generation efficiencies of these technologies). Figure 5.6 illustrates the results of these improvements for the GWP impact category.

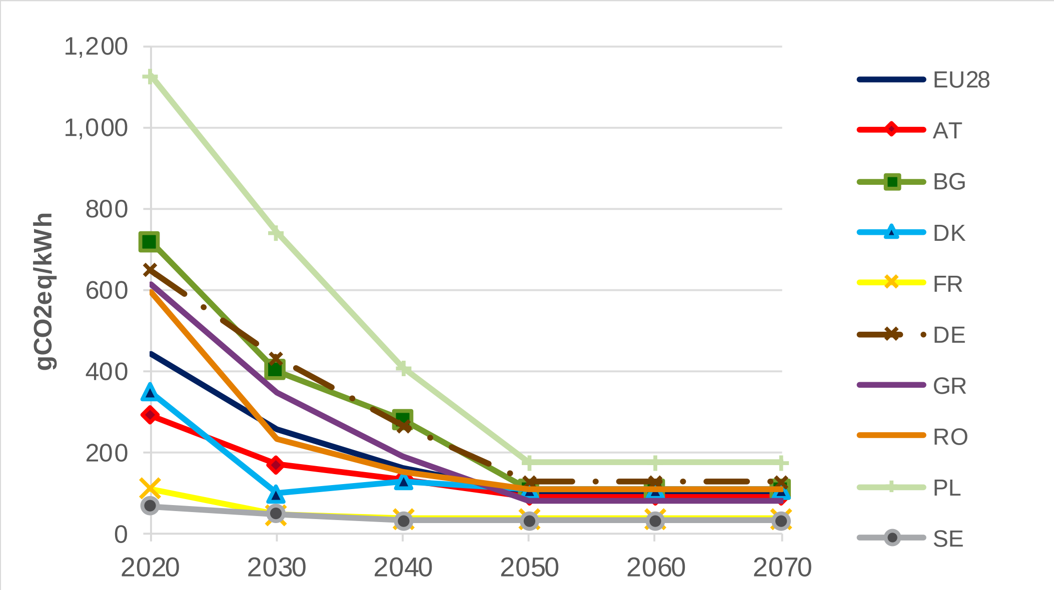
Figure 5.6: Development of the GWP of power generation technologies in the EU28, Baseline scenario



5.2.2 Spatial differences within the EU

The power generation sector differs considerably between EU Member States in terms of fuels and technologies utilised, size and grid integration. All in all, the European power sector is very heterogeneous and thus, consequently, so are the results of the electricity chain LCA for the different Member States. Figure 5.7 provides an overview of the differences for the impact category GWP. All other impact categories follow a similar trend as outlined in the previous chapters. Additional information regarding differences within the EU for other impact categories can be found in Appendix A5.2.2.

Figure 5.7: Development of the GWP of the average electricity mix in different Member States, Baseline scenario

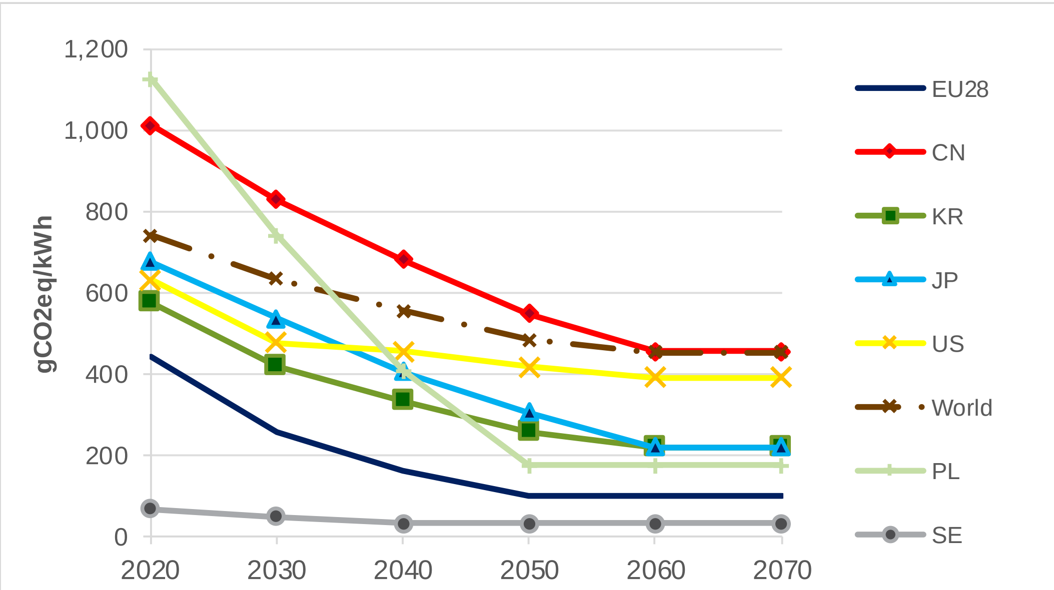


Notes: AT: Austria; DK: Denmark; FR: France; BG: Bulgaria; RO: Romania; DE: Germany; GR: Greece; PL: Poland; SE: Sweden

5.2.3 Countries outside of the EU

Within the study, a number of countries outside of the EU (the US, Japan, China, South Korea and a World Average) were investigated for the time period from 2020 to 2050 due to their significance for the manufacturing of vehicles and key vehicle components (such as the battery). When compared to the EU28 average electricity production, all other countries with a significant share in manufacturing showed higher impacts across the board for all impact categories, except Land Use, Ionising Radiation Potential, Water Scarcity and Ozone Depletion Potential (potentially due to different source, ecoinvent, used for the primary base-year background data for the non-EU countries). This is due to the comparatively high share of fossil fuels in their respective power sectors. Results for GWP impact are shown in Figure 5.8.

Figure 5.8: Development of GWP of power generation in other countries, Baseline scenario



Notes: CN: People's Republic of China; KR: Republic of Korea; JP: Japan; US: United States of America, PL: Poland; SE: Sweden

As in the EU, all the other countries modelled are projected to transition to a more decarbonised power sector in the future and this results in a decline in the GWP impact of generation. Projections for the other countries and, for comparison, for the EU28 average and the two Member States with the some of the highest and lowest GWP are also shown in Figure 5.8. Other impact categories follow a similar trend as observed for the EU countries for GWP.

5.3 Results for fuel production chains

5.3.1 Overview of results

The LCA methodology developed in the study was applied to 60 fuel chains. As described in Section 3.4, the literature review and stakeholder consultation led to the decision to address certain fuel categories through consequential LCA, i.e. differently from the methodologies used so far to support EU policy on fuels (e.g. Renewable Energy Directive). Methodological choices for the different fuel categories are summarised in Section 3.4.1.

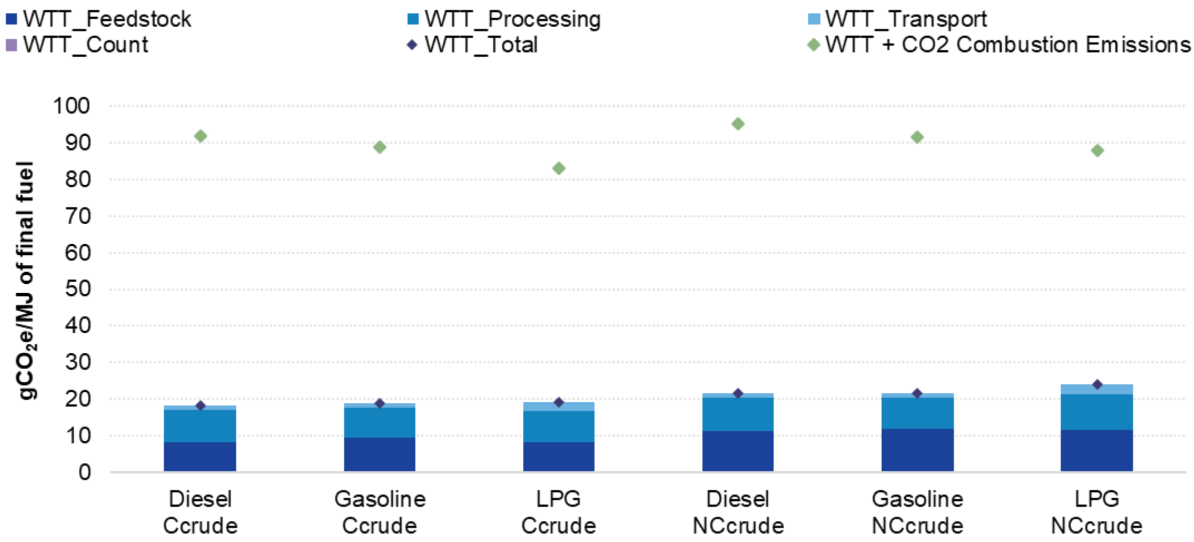
The following sections primarily describe and analyse the results obtained by implementing the methodology developed throughout the project, including novel LCA approaches, which tend to reduce the robustness and comparability of fuel chains.

As described in Section 4.4, however, the possibility to use an energy allocation (instead of substitution) and to remove counterfactual impacts (for secondary fuels) and/or land-use change emissions (for primary biogenic fuels) was built into the implemented fuel chain calculations 3 in order to enhance the robustness and comparability of WTT results used in the main full vehicle LCA calculations and the Vehicle LCA Result Viewers. Some of the following sections provide details about the impact of these alternative methodological choices on results.

5.3.1.1 Primary Fossil Fuels

Figure 5.9 displays the Global Warming Potential (GWP) impacts for liquid primary fossil fuels which are derived from crude oil refining on a WTT basis. Given the significant weight of combustion (exhaust) emissions in the total GWP impact of fossil fuels (see also Section 3.4.1), they are added to the chart (green diamond), based on fuel content (i.e. vehicle efficiency or drive cycle not considered). The use of the ifeu crude refining model did not produce significantly different results, compared to results from the CONCAWE model for GWP; this is further discussed Section 5.3.2.6.

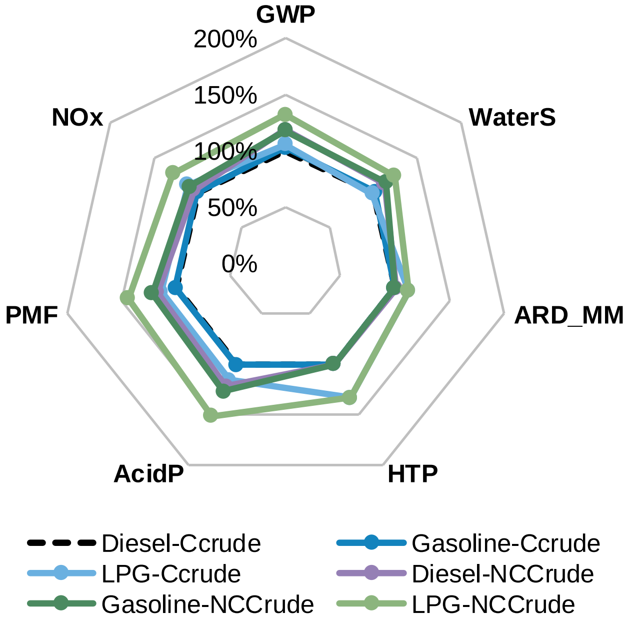
Figure 5.9: GWP impacts: results for liquid primary fossil fuels, based on ifeu refinery model (Co-products addressed via energy allocation)



Notes: Ccrude = conventional crude oil / NCcrude = non-conventional crude oil. *Notes*: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Examples of other LCA impacts from liquid primary fossil fuels are illustrated in Figure 5.10[23]. The trends across fuel chains are similar to those for GWP. LPG from non-conventional crude generally has larger impacts than other chains, especially for Particulate Matter (PMF) and acidification potential (AcidP) - approximately 50% higher than conventional diesel. Non-conventional gasoline and diesel also have moderately higher impacts on acidification and particulate matter than gasoline and diesel from conventional crude, but show no significant differences for NOx, abiotic resource depletion (ARD) or human toxicity potential (HTP).

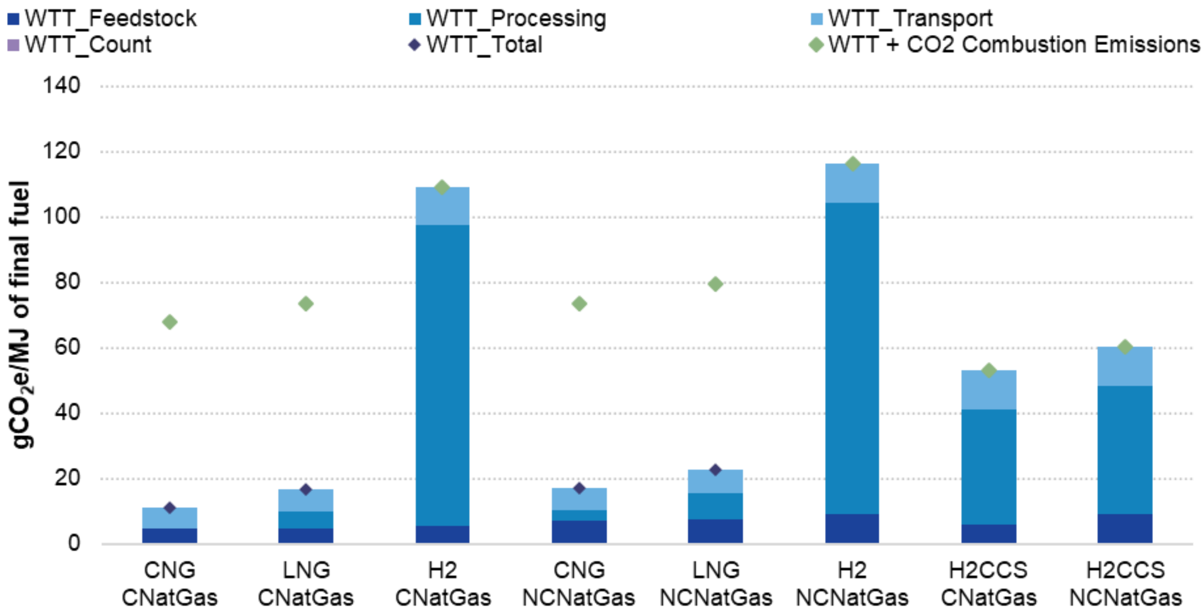
Figure 5.10: Other LCA impacts results for liquid primary fossil fuels



The modelling of conventional CNG/LNG chains and hydrogen produced by the steam methane reforming of natural gas (Figure 5.11) did not yield any significant differences with the results obtained by JEC in its latest WTT report (JEC (Joint Research Centre; EUCAR; CONCAWE), 2018), See Section 5.3.2.7 for additional details. When comparing, hydrogen from natural gas (SMR), with CNG or LNG, it is important to take combustion (exhaust) emissions into account for the latter, given that hydrogen chains do not produce CO_2 upon combustion.

[23] To compare the relative impacts of non-GWP life-cycle impact categories, spider diagrams were constructed. A reference chain was selected, against which all other chains were normalised. The reference chain is therefore given a score of 100% for each impact category. The relative impact score given for the other chains is calculated by dividing their absolute impact scores by the absolute impact score of the reference chain. In some cases, a relative impact score is less than 0%. This is because the absolute impact is negative (whereas it is positive in the reference chain). For example, GWP of ethanol from SRC wood is -4.42 gCO2e/MJ, when this is normalised against the GWP of ethanol from wheat (107.31gCO2e/MJ), the relative impact score is -4%. However, the difference is actually -104%.

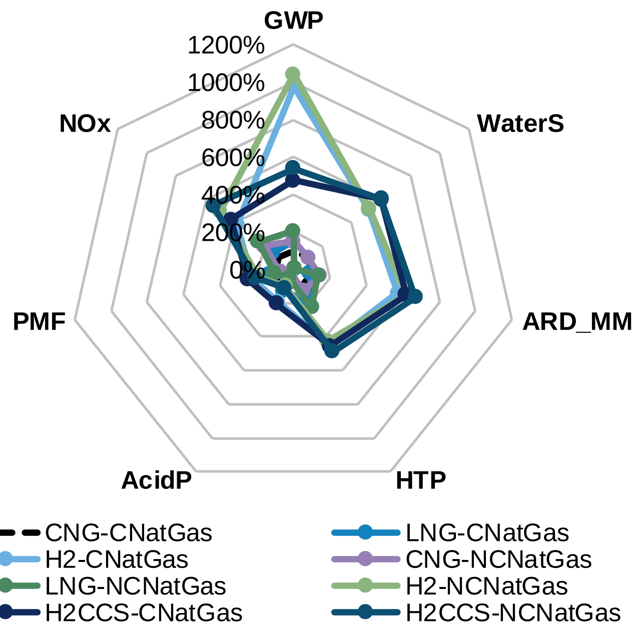
Figure 5.11: GWP impacts: results for gaseous primary fossil fuels (Co-products addressed via substitution)



Notes: CNatGas = conventional natural gas whilst NCNatGas = non-conventional natural gas. The fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

The significantly larger GWP impact observed in Figure 5.11: for hydrogen produced via SMR, compared to other fuels derived from natural gas, is not as marked for non-GWP impacts (Figure 5.12). However, its impact on water scarcity (WaterS), abiotic resource depletion (ARD) and human toxicity (HTP) remains larger.

Figure 5.12: Non-GWP impacts: results for gaseous primary fossil fuels (based on Ecoinvent, JRC and GREET)



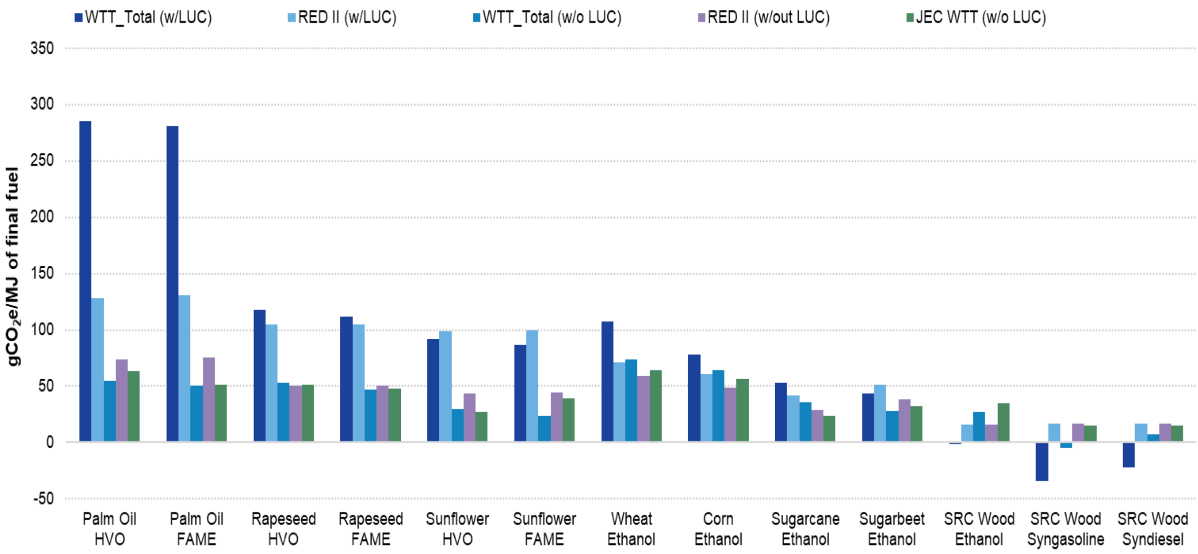
5.3.1.2 Primary Biogenic Fuels

The GWP results for primary biogenic fuels are significantly different from those from JEC, primarily due to the use of Ecoinvent data sets for crop cultivation and LUC emissions (Figure 5.13:). The scope of this study did not allow for an in-depth comparison of the Ecoinvent and JEC datasets to determine precisely the differences and limitations in their assumptions or methodologies. A high-level assessment, however, identified that the inclusion of infrastructure (e.g. agricultural machinery, processing facilities) in the Ecoinvent background data, which is not considered in the JEC dataset, has the biggest effect in the cultivation life-cycle stage. In addition, significant differences between the two data sets regarding the amounts of fertilisers, pesticides and diesel used for cultivation, especially for starch/sugar crops, as well as in the emission factors used to represent the production of these inputs were identified.

As a result of stakeholder consultation it was agreed to include Land-Use Change (LUC) emissions (including SOC emissions) and that LUC emissions would be taken from GLOBIOM (Valin, et al., 2015); these factors are similar to the “iLUC factors” found in RED II. A major difference with RED II, however, is that the GLOBIOM values used in this study are crop-specific whereas RED II uses averages for crop categories (e.g. oilseeds). LUC emissions add a significant GWP burden to primary biogenic fuels. For the majority of fuels the results from our study are similar to those in RED II with ILUC (Figure 5.13). For palm oil the results of this study are significantly higher due to use of an ILUC factor specific to palm oil. GLOBIOM LUC emissions assume a 20-year amortization period; It should be noted that alternative amortization periods (e.g. GWP100) may yield lower LUC emission values, but could not be tested as part of this study.

It is worth highlighting again here, that it was only possible to model a sub-set of the wide-range of possible different biofuel production pathways in this project. For example, it should also be highlighted there is some potential for commercial availability of bio-LPG (e.g. currently being produced in small quantities as a by-product of Neste’s HVO biodiesel production process). However, it was not possible to include this in the current project’s analysis.

Figure 5.13: GWP impacts (with and without LUC): results for primary biogenic fuels and comparison with RED II and JEC WTT (Co-products addressed via substitution | LUC emissions based on GLOBIOM, including SOC)



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Bioethanol chains based on agricultural crops are generally homogeneous with regards to other lifecycle impacts (Figure 5.14), with the exception of human toxicity potential. Acidification and water scarcity also show some notable variations, which reflect the use of agricultural inputs and water consumption during cultivation stages, as modelled in Ecoinvent. Since SRC Wood is modelled as rainfed, its water scarcity impact remains several orders of magnitude lower than other ethanol chains.

No significant differences can be observed for non-GWP impacts of FAME and HVO produced out of the same crop (Figure 5.15), with the exception of ARD for palm oil. Important variations in water scarcity can be seen between palm oil, which is rainfed, and other crops, which require irrigation. The lower HTP score for palm oil can also be explained by cultivation practices (less fertiliser used) and yields (MJ per ha), which are significantly higher for palm plantations than for other feedstocks.

Figure 5.14: Non-GWP impacts: results for bioethanol

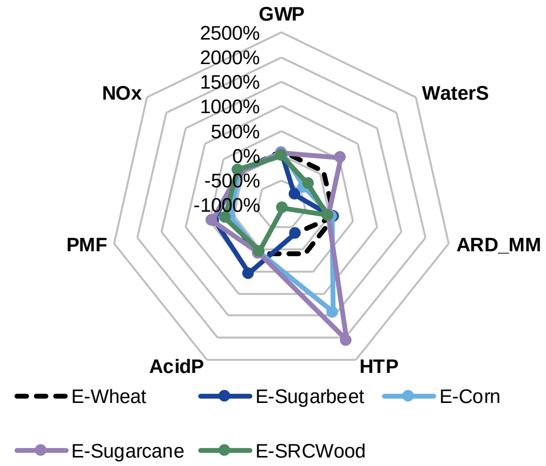
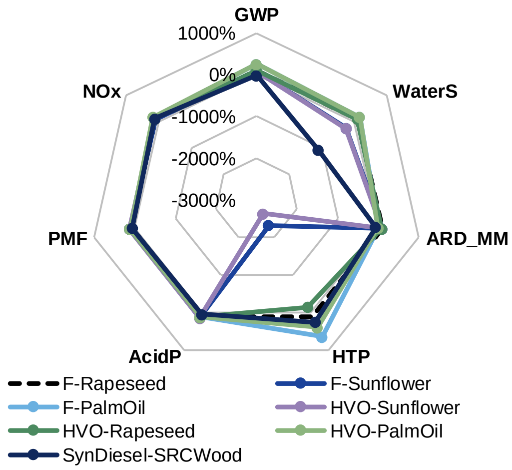


Figure 5.15: Non-GWP impacts results for biodiesel



5.3.1.3 Secondary fossil and biogenic fuels

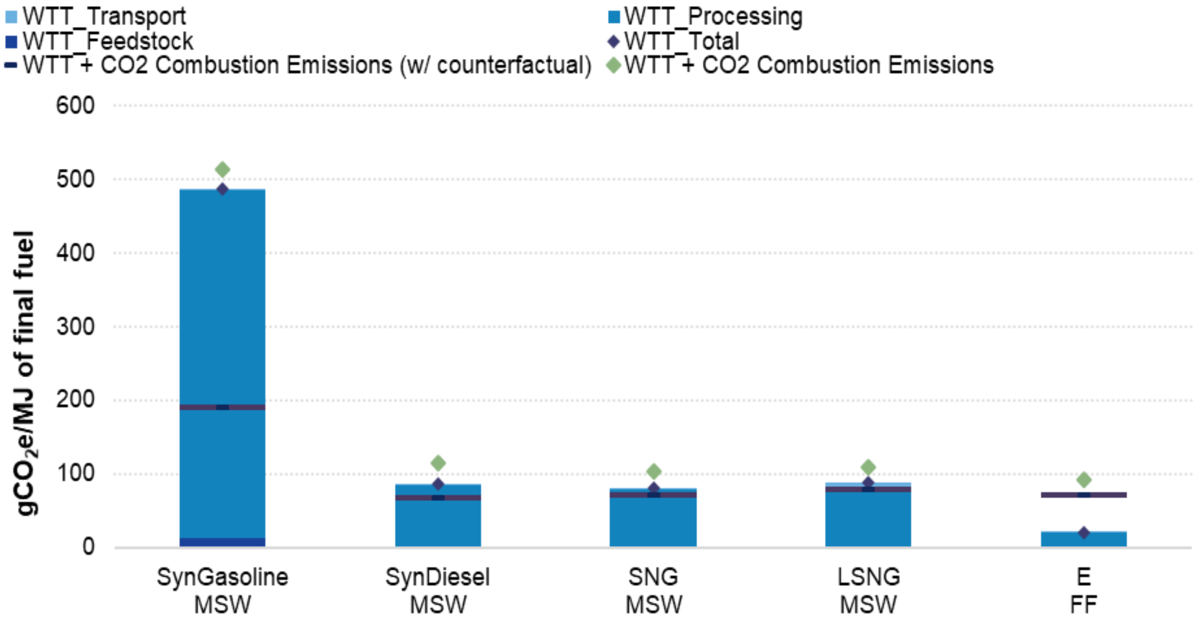
The GWP of the fuels from secondary fossil feedstocks modelled in this study are given in Figure 5.16, and the GWP of the fuels from secondary biogenic feedstocks in Figure 5.17 to Figure 5.19.

The total WTT emissions (dark blue diamond on graph) is the sum of the stacked bars. The WTT + CO_2 combustion emissions (green point marker on graph) adds the CO_2 from combustion (exhaust) of the fuel to the total WTT emissions. Combustion of secondary biogenic fuels (Figure 5.17 to Figure 5.19) does not contribute to GWP so the value of WTT_Total and WTT + CO_2 combustion emissions is the same.

The key methodological aspect explored for the fuels produced from secondary feedstocks was the inclusion of counterfactual emissions (see section 3.4.2.3). The purple line on the graphs (Figure 5.16 to Figure 5.19) represents the WTT emissions + CO_2 combustion emissions when counterfactual emissions are included as well. In some cases the counterfactual emissions are negative, hence the WTT + CO_2 combustion emissions including the counterfactual impacts (purple line) can be lower than the WTT + CO_2 combustion emissions without counterfactual impacts (green diamond). The counterfactual emissions are explored in more detail in section 5.3.2.3.

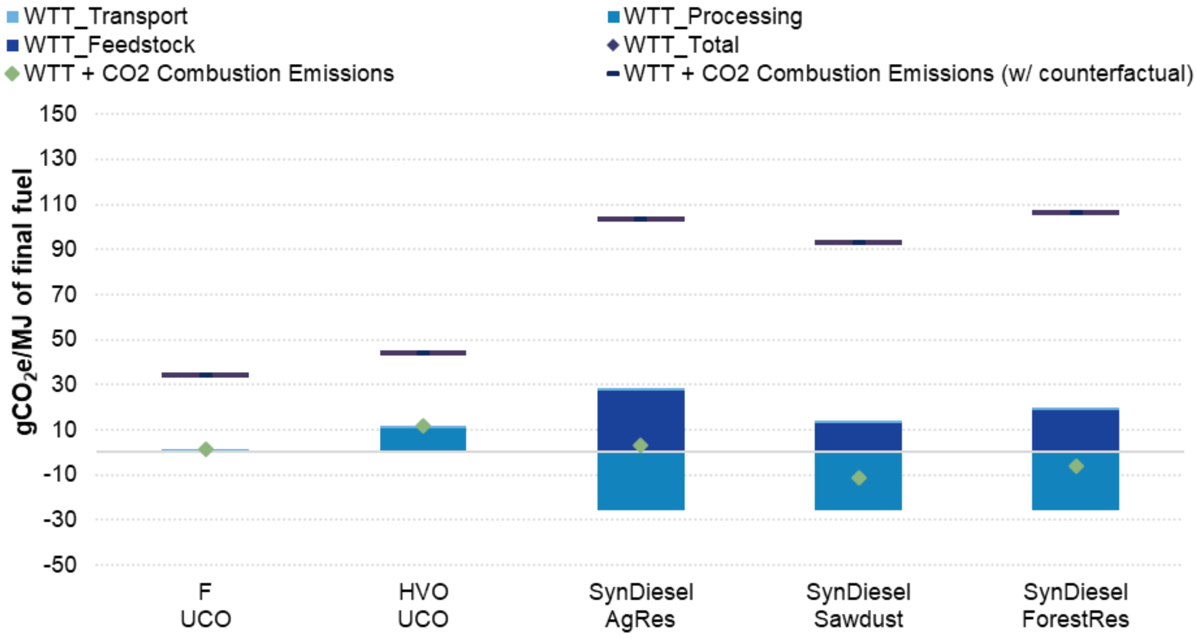
These charts illustrate that for the counterfactual scenarios modelled, the GWP results for fuels produced from secondary feedstocks (both fossil and biogenic) are significantly affected by the inclusion of counterfactual emissions. For fuels produced from MSW, inclusion of counterfactual emissions could reduce the overall GWP impact of the chain, because the GWP of supplying electricity from the grid is lower than the GWP of providing the same amount of electricity by combustion of MSW given the low efficiency of electricity generation from MSW and the fossil CO_2 released when it is combusted. The same trend is seen for ethanol produced from waste industrial gas, because the counterfactual emissions reflect replacing electricity generated from combustion of fossil waste industrial gas with grid electricity. For fuels produced from secondary biogenic feedstocks, inclusion of counterfactual impacts could increase the overall GWP impact of the chain, except for manure. The higher GWP impact of syngasoline compared to syndiesel is due to a lower process efficiency, which amplifies process emissions.

Figure 5.16: GWP impacts of fuels produced from secondary fossil and mixed feedstocks shown with and without counterfactual impacts (Co-products addressed via substitution)



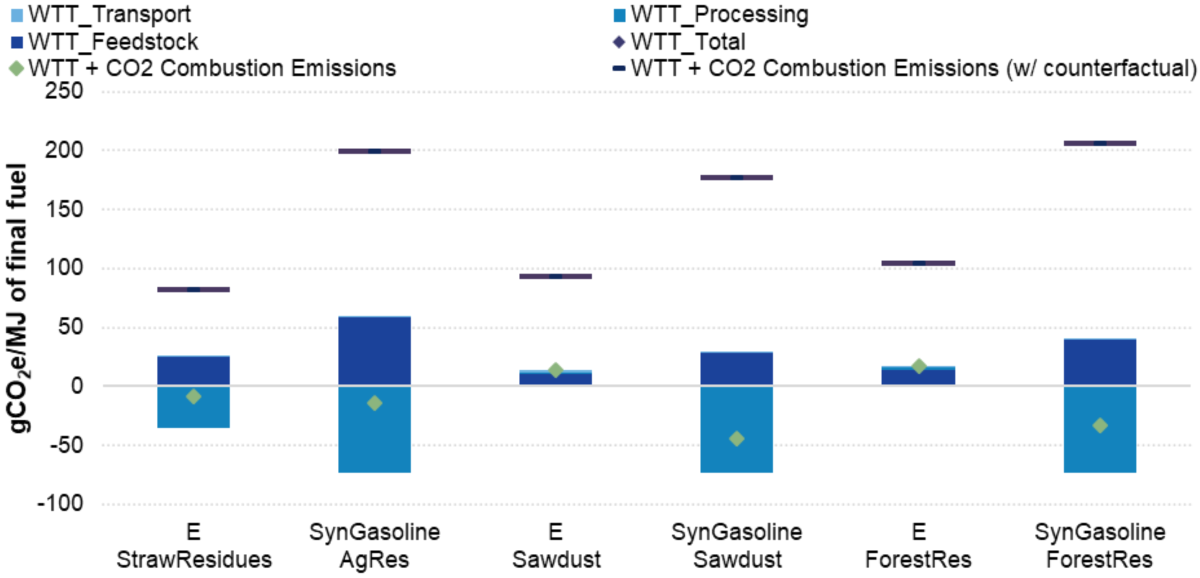
Notes: the fossil fuel comparator is 94gCO₂eq/MJ in FQD and RED2 (European Union, 2018)

Figure 5.17: GWP impacts of diesel fuels produced from secondary biogenic feedstocks shown with and without counterfactual impacts(Based on Ecoinvent and JRC (Co-products addressed via substitution)



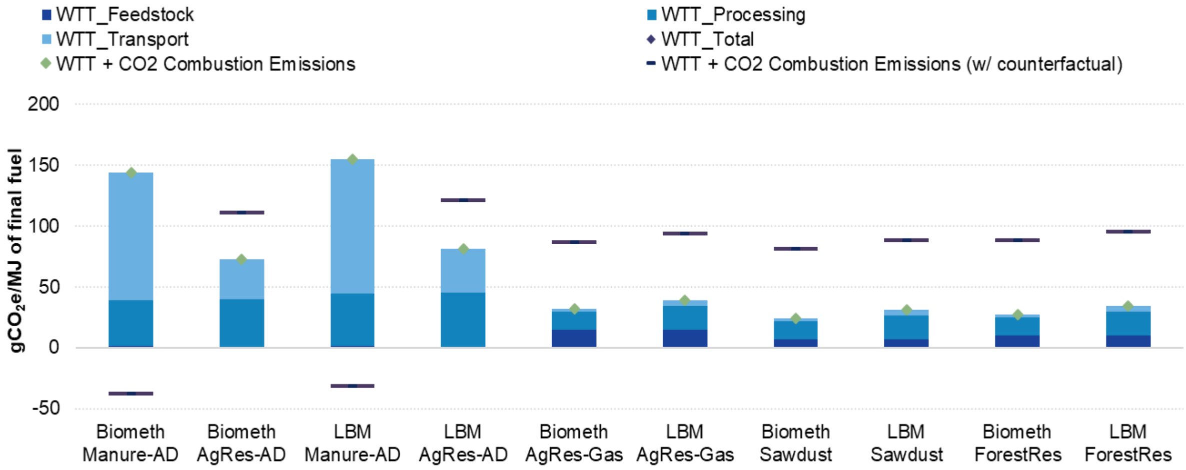
Notes: the fossil fuel comparator is 94gCO₂eq/MJ in FQD and RED2 (European Union, 2018)

Figure 5.18: GWP impacts of gasoline fuels produced from secondary biogenic feedstocks shown with and without counterfactual impacts (Co-products addressed via substitution)



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Figure 5.19: GWP impacts of fuels produced from secondary biogenic feedstocks shown with and without counterfactual impacts (Co-products addressed via substitution)



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

The WTT non-GWP impacts of fuels produced from secondary feedstocks are given in Figure 5.20 to Figure 5.23. These include the counterfactual impacts.

Non-GWP impacts of secondary fossil fuels (Figure 5.20) are homogeneous, with the exception of HTP, for which ethanol from industrial gases (E-FF) and synthetic diesel from MSW have lower scores than synthetic gasoline from MSW, in line with the trend observed for GWP. However, the HTP impacts of SNG and LSNG derived from MSW appear significantly higher than synthetic gasoline. As stated in the previous sections, absolute HTP scores shall be taken with caution.

Non-GWP impacts of biomethane (Figure 5.21) and liquid biomethane (Figure 5.22) are similar and show some convergence with the trends observed for GWP impacts, especially when manure is used. Unlike GWP, the use of agricultural residues via anaerobic digestion also yields lower impacts than via gasification or using other feedstocks.

Finally, significant variations are observed in other lifecycle impacts of ethanol and synthetic gasoline produced out of secondary biogenic feedstocks (Figure 5.23), in line with the results observed for GWP. Variations are particularly important in water scarcity, reflecting the differences in the datasets used to model processing, especially counterfactual scenarios, substitution and process efficiencies.

Figure 5.20: Non-GWP impacts resulting from methodology implementation for secondary fossil fuels

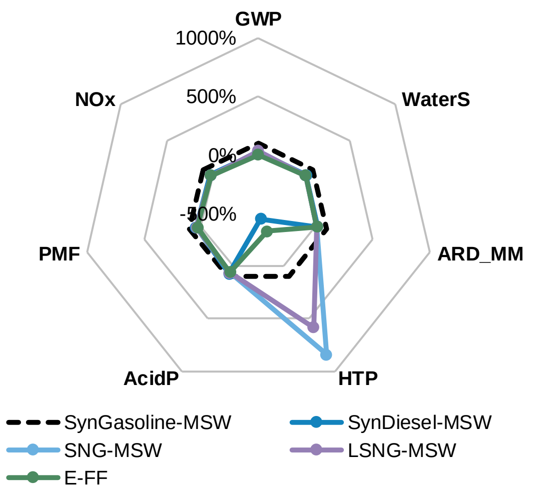


Figure 5.21: Non-GWP impacts resulting from methodology implementation for biomethane

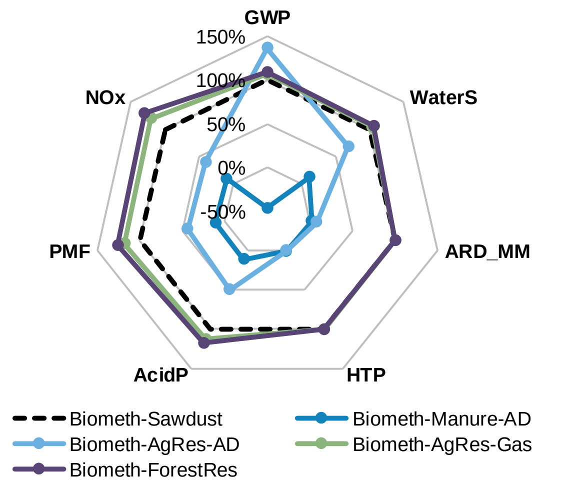


Figure 5.22: Non-GWP impacts resulting from methodology implementation for liquid biomethane

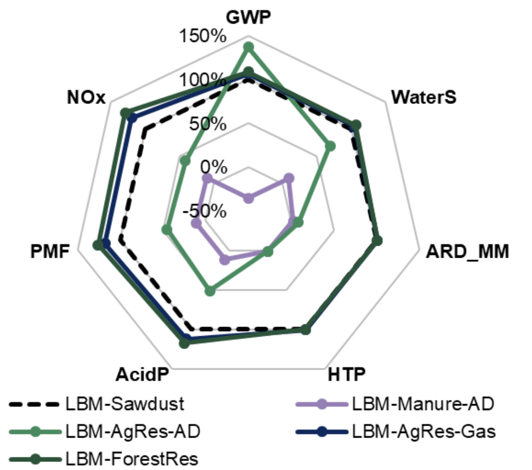
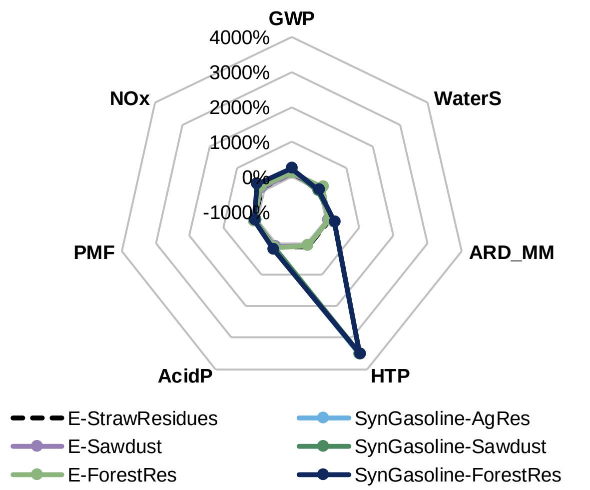


Figure 5.23: Non-GWP impacts resulting from methodology implementation for secondary biogenic fuels (ethanol and synthetic gasoline)



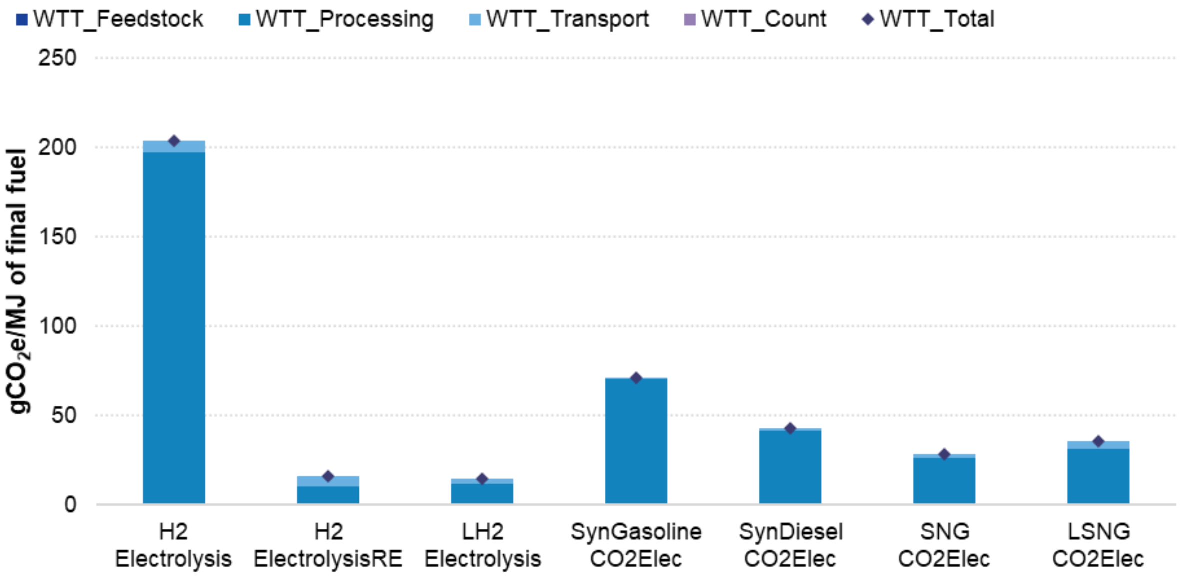
It should be emphasised that only one single counterfactual scenario for each feedstock was modelled in this study, therefore the results are not intended to represent that feedstock or fuel chain comprehensively. In reality, there may currently be sufficient volumes of many secondary feedstocks so that their use for fuel production today would not divert them from any existing use, in which case counterfactual emissions would be zero. The results presented in this study can therefore be considered as a "worst-case" scenario, representing a situation where all secondary feedstocks already have a productive use, and the supply of secondary feedstocks would be inelastic. Nevertheless, the results highlight that there could be substantial environmental impacts if secondary feedstocks are diverted from other uses, a situation which could become increasingly prevalent in the future in some locations as feedstock supplies become constrained. Given that counterfactual impacts are very specific to the exact feedstock being used, and the time and location of its use, it is not possible to generalise these conclusions to whole categories of feedstocks. However, the insights gained from this study highlight that the risk of counterfactual impacts could be substantial and should be investigated in more detail for certain feedstocks. The impacts of using this counterfactual methodology and results for particular fuel chains are explored in more detail in section 5.3.2.3.

5.3.1.4 E-Fuels

The GWP of all e-fuels modelled in this study are shown in Figure 5.24. Two fuel chains for hydrogen production via electrolysis are modelled: H2-Electrolysis, where the electricity used for electrolysis and for compression of the hydrogen is the average grid mix and H2-ElectrolysisRE where renewable electricity is used. All other e-fuels are modelled using renewable electricity for electrolysis, compression and liquefaction.

Figure 5.24 illustrates the strong dependency of the GWP of e-fuels on the GWP of the electricity used in fuel production – grid average electricity with a higher GWP is used in H2-Electrolysis and renewable electricity with a much lower GWP for H2-ElectrolysisRE. As noted in section 3.4.2.4 the CO_2 used in the production of the syngasoline, syndiesel and SNG from electrolysis is assumed to come from a waste stream that would have otherwise been emitted to the atmosphere. Therefore, no environmental impacts are associated with the emission of CO_2 from the combustion of e-fuels. Emissions from the capture of this CO_2 are taken into account.

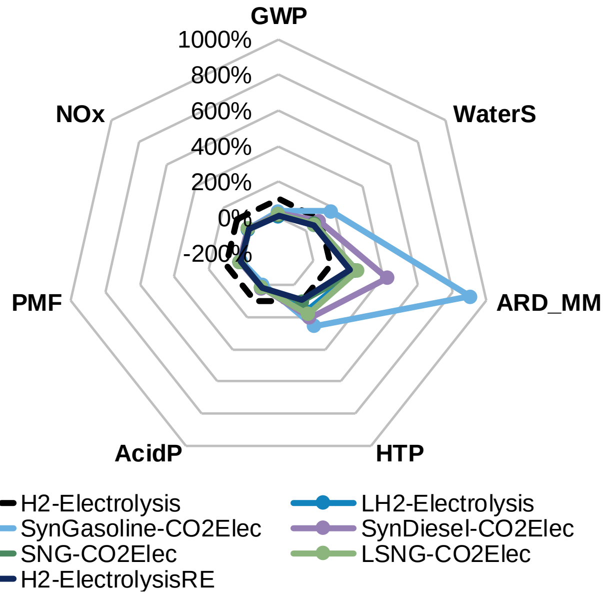
Figure 5.24: GWP impacts resulting from methodology implementation for e-fuels (Co-products addressed via substitution | grid electricity for H2 Electrolysis | renewable electricity for all other e-fuels)



Notes: For the results in the graph above, H_2-Electrolysis is modelled using an average grid mix for Europe, while the other chains, including H2-ElectrolysisRE, are modelled using renewable electricity for their production (including the electrolysis, compression and liquefaction). The fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

The non-GWP impacts of e-fuels are illustrated in Figure 5.25. As noted previously, the lower efficiency for the production of syngasoline compared to syndiesel means higher impacts are typically seen for the syngasoline chain. The higher impacts from syngasoline, syndiesel, LH_2 and SNG in abiotic resource depletion and HTP result from the worse performance of renewable electricity compared to grid electricity in these impact categories.

Figure 5.25: Non-GWP impacts resulting from methodology implementation for e-fuels



5.3.2 Analysis of the implementation of methodological choices

5.3.2.1 Influence of background data on results

Background data is an essential element of an LCA. It includes energy and materials that are inputs to the systems in the form of aggregated datasets, derived from other certified studies. In this study, most background data are taken from Ecoinvent and includes the impact of infrastructure, for example, in cultivation of crops this includes the agricultural machinery and in processing steps this includes the construction of the facilities where the fuels are produced. The exception is electricity where (as discussed in Section 3.3 and 4.3) background data came from the Umberto electricity model. More details of the background LCI database are in Section 4.2. Within the complete LCI, there were numerous instances where approximations had to be made in order to match foreground and background parameters, due to the exact parameter not existing in Ecoinvent. An example of this is shown in Table 5.1, where the same background data parameter from Ecoinvent is used for both alpha-amylase and gluco-amylase in the fuel chain modelling, whereas in the JRC default values each amylase has a different background data value. Note, the JRC default values are based on JEC datasets (JEC - Joint Research Centre; EUCAR; CONCAWE, 2014a).

Table 5.1: Illustrative example of differences in background data sets

Parameter	Ecoinvent* (gCO_{2e}/kg)	JRC (gCO_{2e}/kg)
Alpha-amylase	5700	1000
Gluco-amylase		7500

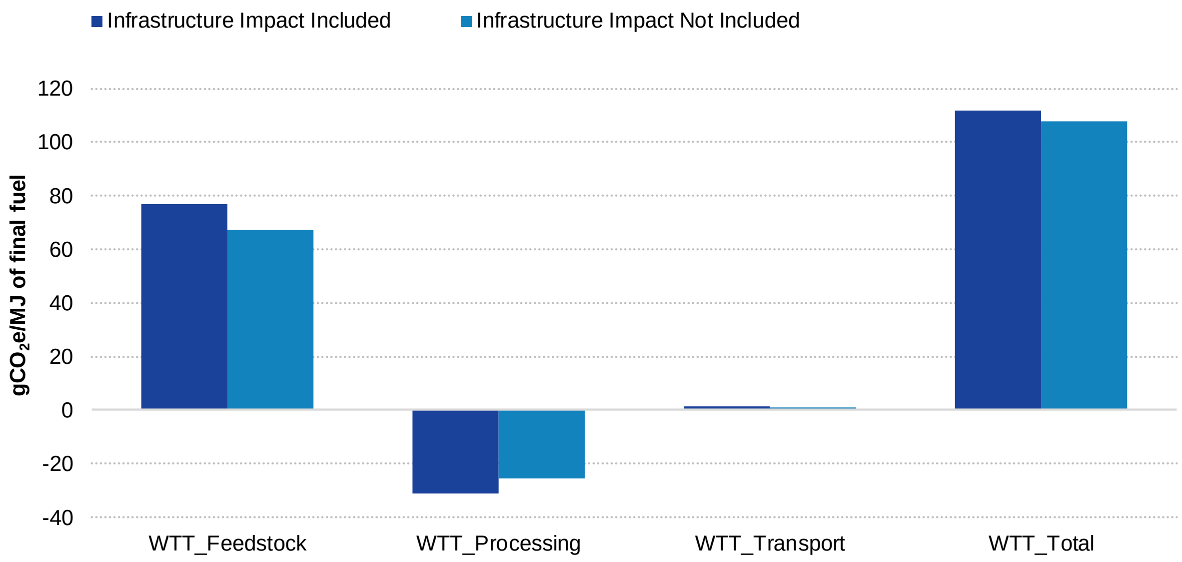
Notes: * Ecoinvent flow for both: Enzymes {RER}| enzymes production | APOS, U

Though the methodology for calculating GWP is fairly standardised, for other impact categories the methodology and thus background data values can differ. Therefore the assessment on the influence of background data on the results of this study focuses on GWP; this has the additional advantage that it allows for a comparison to the default background data set used by the JRC for which only GWP impacts are calculated.

The JRC default values (Edwards, et al., 2019) do not include the impact of infrastructure in the background data, therefore the first stage of this comparison looks at the effects of including/excluding infrastructure on results for fuel chains, using FAME from Rapeseed as an illustrative example. Figure A61: shows that including infrastructure increases emissions in the feedstock and processing steps. In the former, there is an increase of 9.2 gCO_{2e}/MJ FAME (12.2%) from the inclusion of infrastructure (e.g. agricultural machinery) associated with agricultural processes such as sowing, application of fertiliser, tillage, etc. For these individual components of rapeseed cultivation, the difference in GWP when infrastructure is included can be as much as 60% for some operations (e.g. irrigation).

In the case of processing, inclusion of infrastructure reduces the GWP by 5.88 gCO_2e/MJ FAME. The stages involved in the processing of rapeseed to FAME are oil extraction and refining and transesterification, the former of which has a negative GWP under the substitution methodology outlined in Section 3.4.1. While the effects of infrastructure have similar relative impact on both stages, the absolute difference is greater for the oil extraction and refining step. This is due to the co-product rapeseed cake, where the associated infrastructure impact increases the GWP of this flow by 5.84 gCO_2e/MJ (which was modelled as wheat grain feed), this is due to the associated agricultural process as described above. However, as rapeseed cake receives a substitution credit in this model, the result is a more negative GWP for WTT processing. Overall the difference in the total WTT GWP impact from inclusion of infrastructure is an increase of 3.81 gCO_2e/MJ FAME (3.4%).

Figure 5.26: Effects of including infrastructure impacts on GWP for FAME from Rapeseed, based on the foreground data used in this study



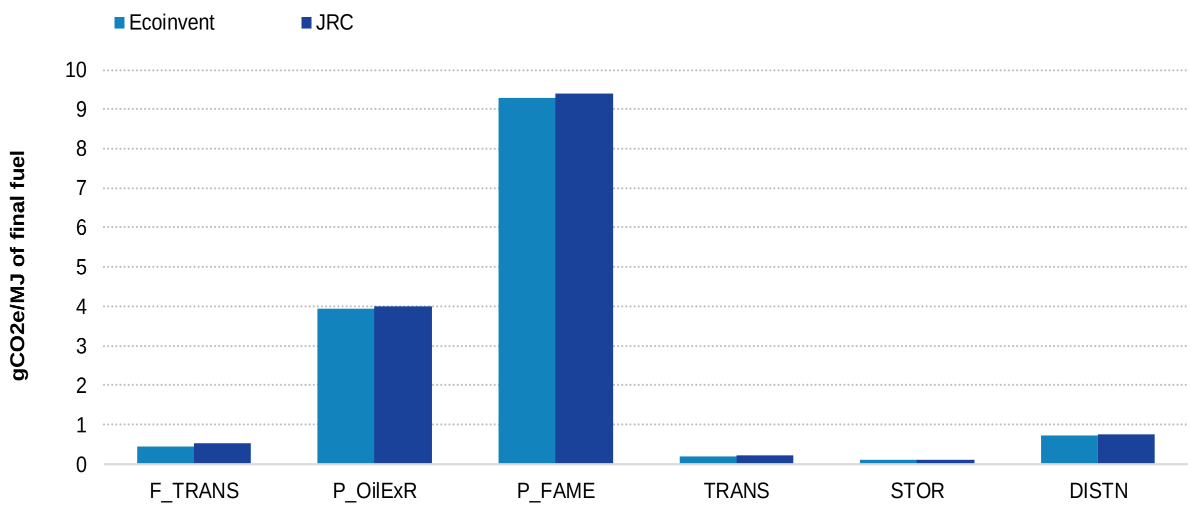
Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Another key difference between the methodology adopted in this study and that used by the JRC, and adopted in RED is the approach to multi-functionality; in this study this is primarily dealt with by substitution, whereas in the JRC analysis and the RED it is dealt with by energy allocation. A further analysis was therefore carried out to check the impact of inclusion of infrastructure if an energy allocation rather than substitution approach is taken. It was found that where the methodological choice is energy allocation, the effects of including infrastructure impact on the processing life-cycle stages are significantly smaller, with an increase of only 0.46 gCO_2e/MJ. However, the overall effect on WTT GWP impact, in absolute terms (an increase of 4.9%), is slightly greater when using energy allocation compared with substitution. This difference is due to the negative GWP in processing under substitution, due to co-products, which counters the increased GWP seen in the other stages. Generally, where there is a co-product present, which is modelled as a flow with high agricultural processes (e.g. sunflower cake), the impact of removing infrastructure is expected to be higher under an energy allocation.

In general, cultivation emissions of primary biogenic feedstocks in this study were higher than those reported by the JRC: This can partially be attributed to the inclusion of infrastructure impact in the background datasets used in this study, highlighting that infrastructure emissions are important for life-cycle stages involving agricultural processes. There are, however, also significant differences in the foreground data used in Ecoinvent, compared to JRC, in relation to agricultural practices for crop cultivation (e.g. the amount of fertilisers or pesticides used per ha or per ton of feedstock). For lifecycle stages where the same foreground data is used in this study as in the JRC analysis (processing and transportation steps) a further comparison is made below of the impact of using different background data sets

In order to isolate the impact of the background data set, results from this study for FAME from rapeseed were adjusted to put them on the same methodological basis as the JRC analysis i.e. an energy allocation basis and excluding infrastructure. Despite some significant differences in individual background data values, particularly for chemical flows, the overall effect on WTT GWP of the fuel chain is minimal, as shown in Figure 5.27. Using the JRC background data results in a WTT GWP 0.36 gCO_2e/MJ FAME (0.31%) higher than if using Ecoinvent background data set, for the life-cycle stages shown in Figure 5.27. This small variation can be attributed to the limited difference in GWP values for energy flows, and the fact that the chemical inputs are generally several magnitudes smaller than the energy inputs.

Figure 5.27: Effect of differing background datasets on GWP impact of life-cycle stages for FAME from rapeseed with the same foreground data



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

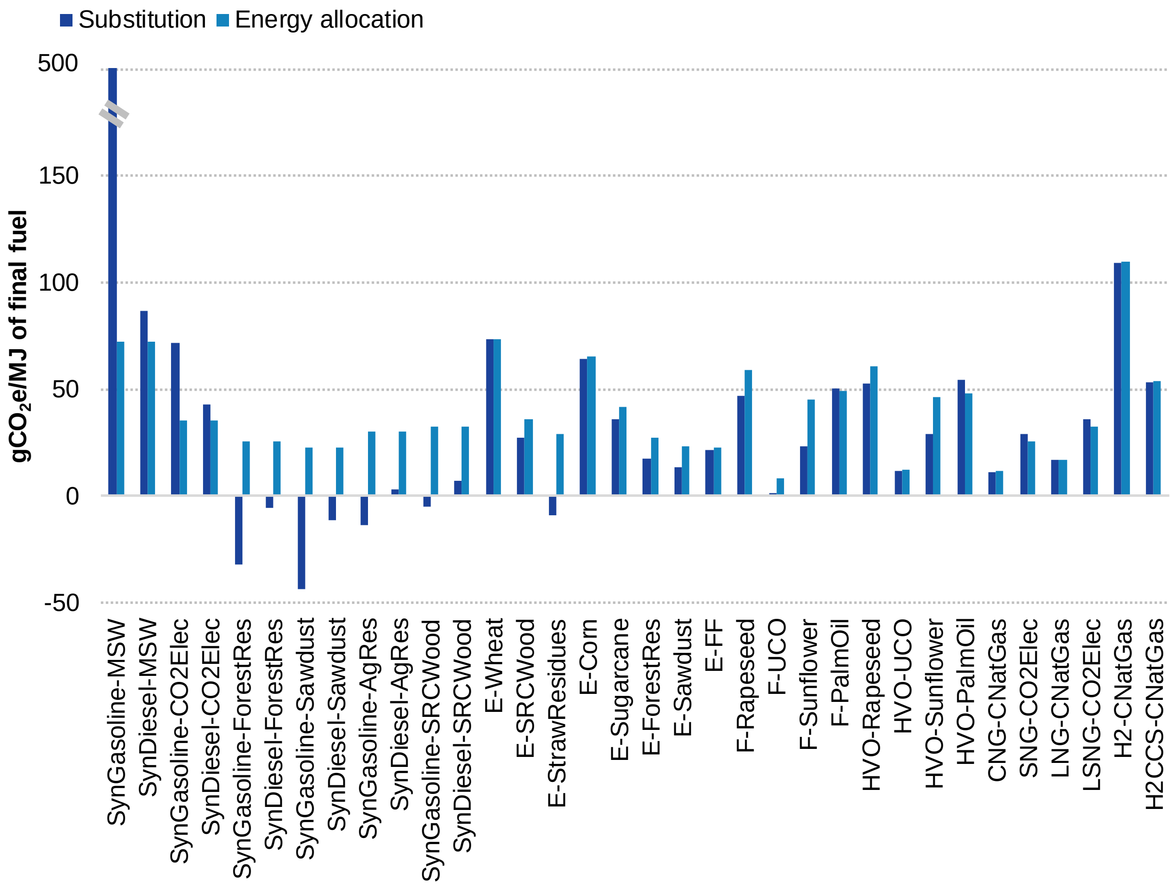
5.3.2.2 Multi-functionality: influence of substitution method on results

5.3.2.2.1 Global Warming Potential (GWP)

For all fuels apart from those produced in an oil refinery, multi-functionality was dealt with using a substitution method. In order to investigate the impact of this methodological choice on overall results, the GWP impacts for fuel chains producing multiple products were also modelled using energy allocation and compared to the results generated using the substitution method (Figure 5.28). Greater information of the substitution method and energy allocation are given in Appendix A3.7.3 To simplify the comparison, the results presented do not include impacts from LUC and counterfactuals, although excluding counterfactual impacts does result in a very high GWP for fuels produced from MSW.

Broadly for all fuel chains, apart from the synthetic fuel chains, results between the two multi-functionality methods are similar. The results for synthetic fuels differ substantially between the two allocation methods because there are several co-products with similar yields (syndiesel, syngasoline and electricity). Therefore, differences in the allocation of emissions between these products has a big impact on the overall results for each individual product. However, it is important to stress that the fuel chains should only be compared against each other if they are assessed under the same LCA methodology, including how multi-functionality is treated, e.g. results for fuel chains calculated using an energy allocation should not be compared to results from fuel chains using a substitution approach to multifunctionality.

Figure 5.28: GWP impacts of fuel chains with co-products, assessed using a substitution method and an energy allocation

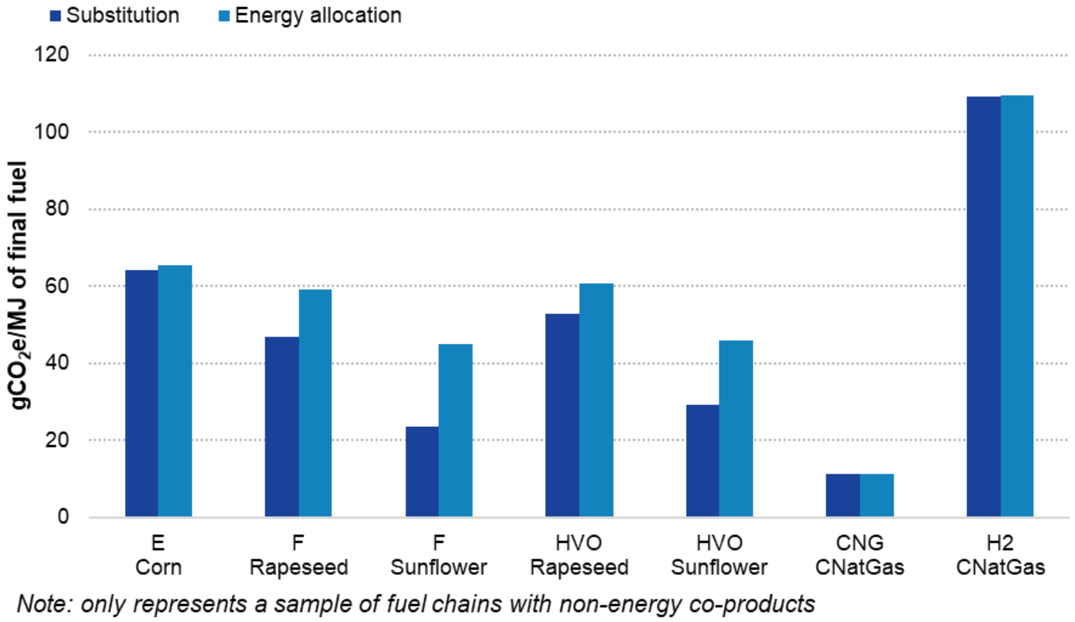


Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Of the fuel chains modelled, the methodology for treating multi-functionality had the greatest absolute impact on GWP scores for synthetic fuels. In the specific case of syngasoline, foreground data also impacted results significantly: As it was not possible to source syngasoline specific data, foreground data based on a process optimised for syndiesel production was used and adapted. This means that for syngasoline chains, a greater amount of syndiesel is produced as a co-product than syngasoline (the main product). While the absolute inputs and outputs entering the production step are the same for both syngasoline and syndiesel production from a given feedstock, output yields change depending on which is considered the main product of that chain – higher efficiency for syndiesel production compared to syngasoline. The effects of non-differentiated foreground data are of a greater concern using the substitution method, as it models the impacts of a fuel chain in isolation. Conversely, in an energy allocation, impacts are divided equally per total MJ produced in the entire process, regardless of the main product. Therefore, as process-specific data could not be sourced for syngasoline production, using an energy allocation may be more appropriate for the synthetic fuel chains.

For fuel chains producing non-energy co-products alongside the main fuel, the substitution method generally results in a lower GHG impact for the main fuel, compared to the energy allocation methodology (Figure 5.29). This is probably due to a combination of the typically low energy content of these co-products, and the relatively high impacts associated with the substituted products. For example, rapeseed cake, produced both in HVO-Rapeseed and F-Rapeseed chains, generates a substitution credit equivalent to 41.3 gCO_2e/MJ of rapeseed oil. Comparatively in an energy allocation, the rapeseed cake accounts for 40% of the total energy content of all products arising from rapeseed oil extraction, and therefore leaves the system with 30.7 gCO_2e/MJ.

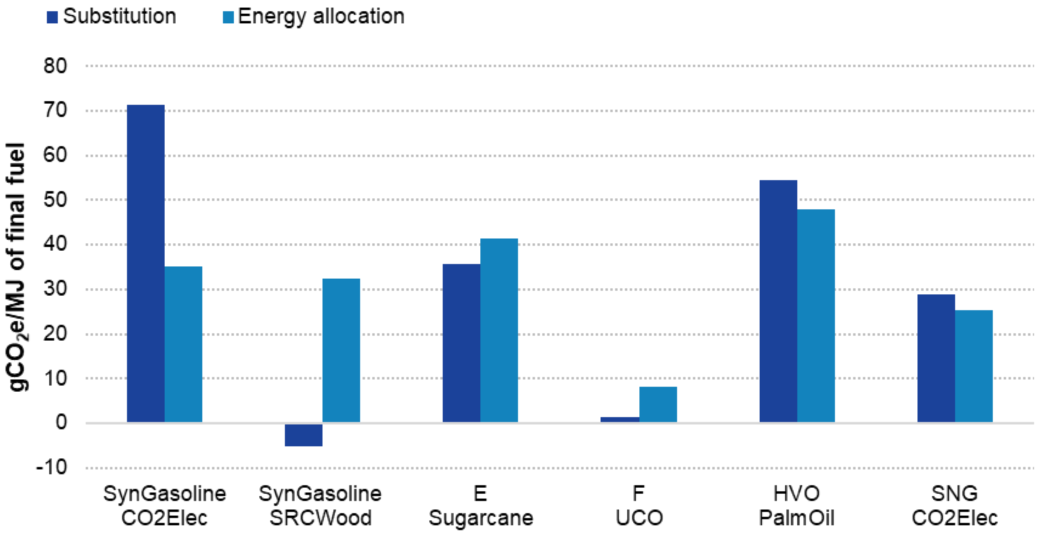
Figure 5.29: Impact of multifunctionality approach on GWP impacts of fuels with non-energy co-products



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Fuel chains which produce at least one energy co-product do not exhibit a homogenous trend in the impact of using an energy allocation versus a substitution method. Some chains have a greater impact when a substitution methodology is used and others when an energy allocation methodology is used (Figure 5.30). In some instances, fuel chains have a net negative impact under the substitution method. This is because the displaced impacts related to the co-product (i.e. the substitution credit) outweigh the gross impact of producing the fuel and its co-products. In an energy allocation, net negative impacts cannot be generated, as co-products are allocated a share of the emissions only up to the point of their production.

Figure 5.30: Impact of multifunctionality approach on GWP impacts of fuels with energy co-products

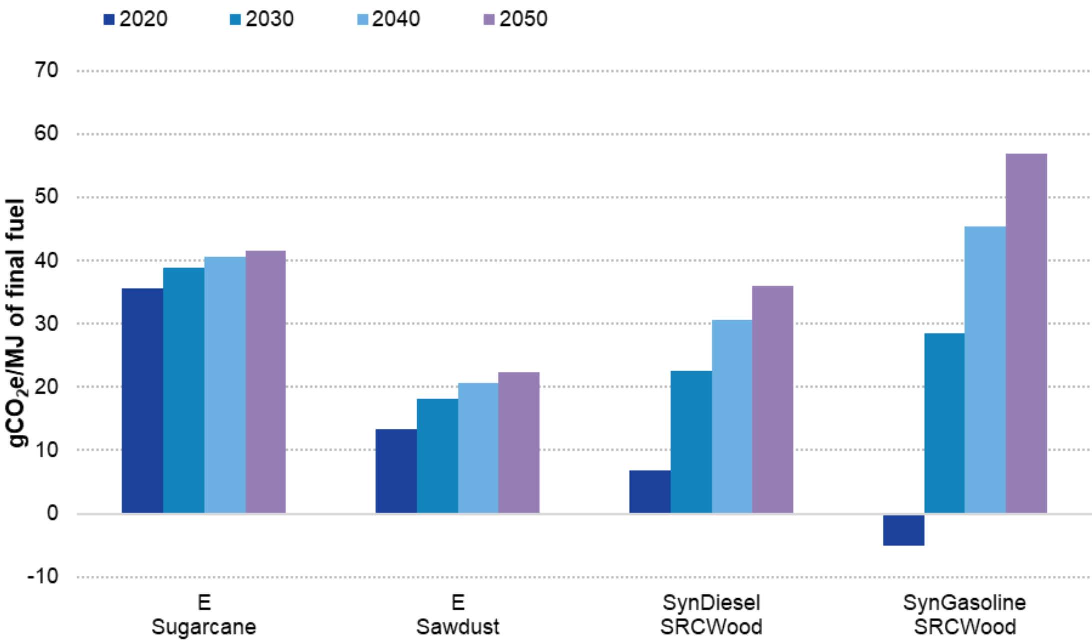


Notes: this graph only represents a sample of fuel chains with energy co-products. The fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

In the substitution method, the credit assigned to co-products can vary over time, as the impacts of producing the displaced products change with time (Figure 5.31). For example, several chains produce electricity as a co-product, and therefore the substitution credit given to the system changes over time.

As grid mixes continue to decarbonise, the credit for co-produced electricity becomes smaller and therefore the WTT impact of the transport fuel increases over time (if all else remains unchanged). The *attractiveness* of a fuel can therefore vary with time. For example, syngasoline produced from SRC wood has a negative GHG impact in 2020, but this rapidly rises to nearly 60 gCO_2e/MJ of final fuel by 2050 (Figure 5.31).

Figure 5.31: GWP impacts of fuels between 2020 and 2050, where the substitution credit changes with time



Notes: this graph only represents a sample of fuel chains.

An advantage of using the substitution method is that it allows for temporal variations in the wider energy system to be taken into account; an aspect which cannot be captured using an energy allocation method. This is especially relevant when power is produced as a co-product, as substantial changes in the environmental impacts from electricity production are anticipated over the next decades. In an energy allocation scenario, the co-produced electricity will be allocated the same share of the total impacts over time, even if the grid electricity it is replacing is decarbonising. Therefore, it is conceivable that the impacts allocated to the co-produced electricity using energy allocation could become higher than the grid average. This suggests that when considering large-scale changes over significant timelines, using a substitution methodology could be a useful tool to examine the system-wide consequences of alternative fuel production.

5.3.2.2.2 Other impacts

The effect of the multifunctionality approach on non-GWP impacts is illustrated in Figure 5.32 to Figure 5.37 for a selection of fuel chains and impacts. In all the cases illustrated, NOx emissions and PMF are not significantly affected by the choice of substitution or energy allocation. With the exception of synthetic gasoline produced from hydrogen and CO_2 (syngasoline-CO_2elec) and corn ethanol, acidification scores are also not significantly impacted by the methodological choice for multifunctionality. In the case of corn ethanol (Figure 5.37), a non-energy co-product is generated (DDGS), but unlike GWP (Figure 5.28), the acidification score is higher when using energy allocation, compared to substitution.

Water scarcity shows significant variations, but no convergence as substitution may either lead to water scarcity score being significantly above, below or the same compared to energy allocation. Variations are particularly important among primary biogenic fuels, although, in the case of corn and wheat, the same kind of by-products (feed substitute) is produced. However, the water scarcity impact from the data set used to model crop cultivation is significantly higher (almost seven times) for wheat than for corn. Further, the water used in processing of wheat is about 50% higher than for corn. Due to differences in the relative amounts of co-products produced (higher in the case of wheat on a per MJ basis) the subsequent “water scarcity credit” obtained by wheat through substitution is higher than corn.

Figure 5.32: Effect of multifunctionality approach on non-GWP impacts (Wheat Ethanol)

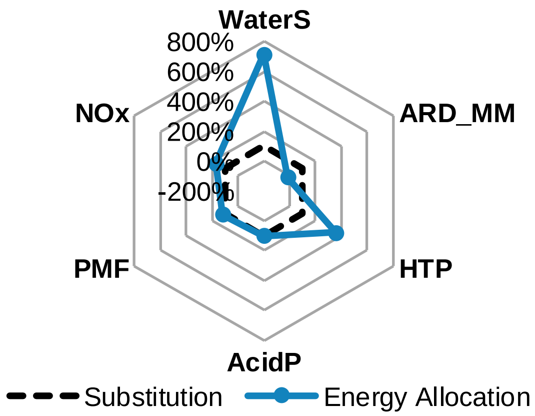


Figure 5.33: Effect of multifunctionality approach on non-GWP impacts (Syngasoline-CO2elec)

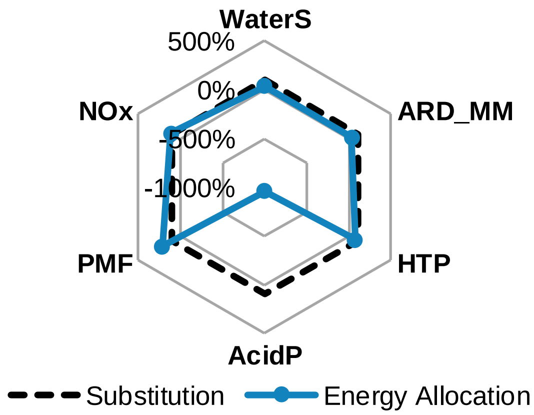


Figure 5.34: Effect of multifunctionality approach on non-GWP impacts (Rapeseed FAME)

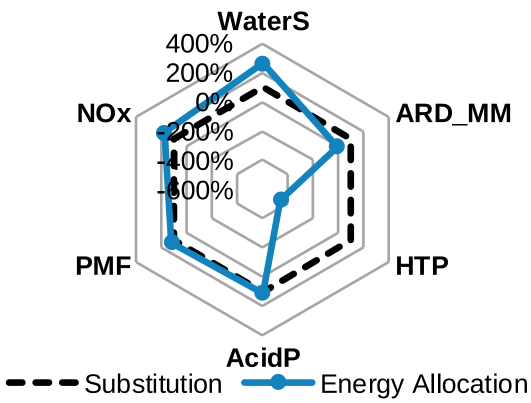


Figure 5.35: Effect of multifunctionality approach on non-GWP impacts (Syndiesel-ForestRes)

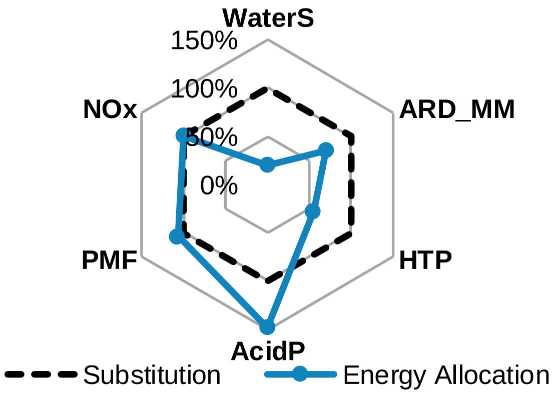


Figure 5.36: Effect of multifunctionality approach on non-GWP impacts (Syngasoline-MSW)

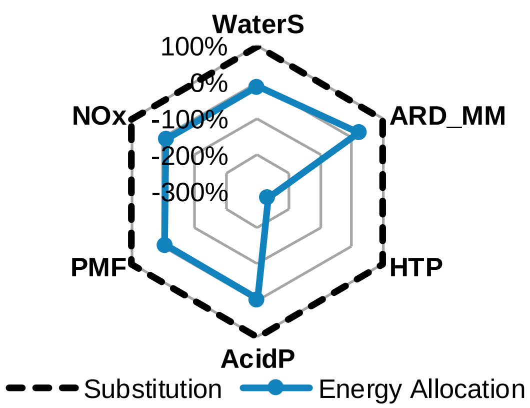
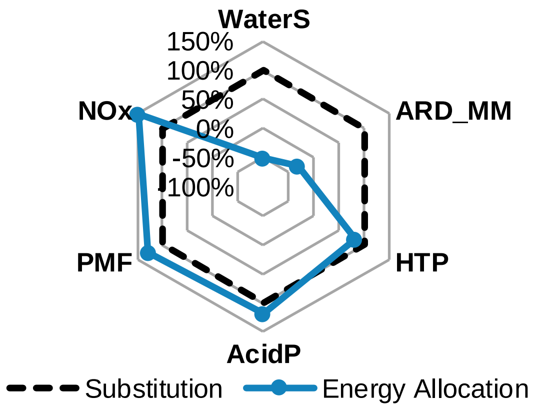


Figure 5.37: Effect of multifunctionality approach on non-GWP impacts (Corn Ethanol)



5.3.2.2.3 Synthesis

Results show that the methodological choice for multi-functionality may lead to important variations in how the environmental impacts (both GWP and non-GWP) are assessed for a significant number of fuel chains.

Dealing with multi-functionality by substitution requires more modelling/assumptions and calculation steps than energy allocation, and hence leads to some limitations in the results which should be highlighted:

- Detailed knowledge and modelling of market dynamics is required to assess which existing product would be displaced by the co-product of the fuel production chain, taking into account saturation of the market, supply and demand elasticities etc. This could vary for a given co-product according to where it is produced, time of year etc. The quality and properties of the co-product compared to the product it is replacing must also be taken into account in order to understand whether the co-product can substitute the existing product in the market on a 1:1 basis. The impacts associated with the production of the equivalent, conventional product, and hence the size of the co-product credit, can also vary over time, geography etc.
- In the fuel chain modelling in this study a single common use of the co-product is modelled, but no detailed modelling has been carried out to determine whether this is the most likely use of the co-product.
- In this study, a 1:1 displacement (on a mass basis for non-energy co-products and energy basis for energy co-products) is assumed for all co-products to the equivalent product which they replace in the market. For example, dried distillers grains with solubles (DDGS), sunflower cake, rapeseed cake and palm oil cake, are all assumed to displace 1 unit of animal feed (produced from wheat). However, there is likely to be variation in the nutritional content of these co-products which means that more or less than 1 equivalent unit of animal feed may in reality be displaced.

This study has not highlighted any major problems with the existing use of energy allocation. However, overall, the substitution method provides insight into the system-wide impacts of alternative fuel production and how these could change over time. However, energy allocation is substantially more straight-forward to implement, as it relies only on physical properties of co-products which can be easily measured, and the result does not vary according to plant location or local economic conditions. In general, when comparing results from LCA studies it is important that the methodology used is the same, so that results reflect changes between systems rather than methodological changes. This is particularly the case when methodological changes are known to have a big impact on the system, as in the case of synthetic fuels under different approaches to multi-functionality. Therefore, in order to compare alternative fuels with fossil fuels, the same allocation method should be employed.

A sensitivity analysis for the overall vehicle LCA is provided in later Section 5.5.8, to illustrate the impacts on GWP of switching between the different allocation methods modelled, for the fuel blends used.

5.3.2.3 Use of counterfactual scenarios for secondary fossil and secondary biogenic fuels

5.3.2.3.1 Global Warming Potential

As described in section 3.4.2.3, the scope of the analysis for secondary fossil and secondary biogenic fuels includes the impacts of diverting that feedstock from an existing use (termed 'counterfactual use') and replacing any useful products (such as heat or power) that it generated. Together these two terms represent the environmental impact of using that secondary feedstock for fuel production (see Figure 3.7 in section 3.4.2.3). These are known as the counterfactual impacts and are represented by the purple bar (WTT_Count) in Figure 5.38 to Figure 5.40. In these graphs the sum of all of the bars (including counterfactual emissions) gives the total WTT emissions (WTT_Total). For secondary biogenic fuels the GWP from the CO_2 combustion emissions is zero so the WTT + CO_2 combustion emissions has the same value as the WTT_Total.

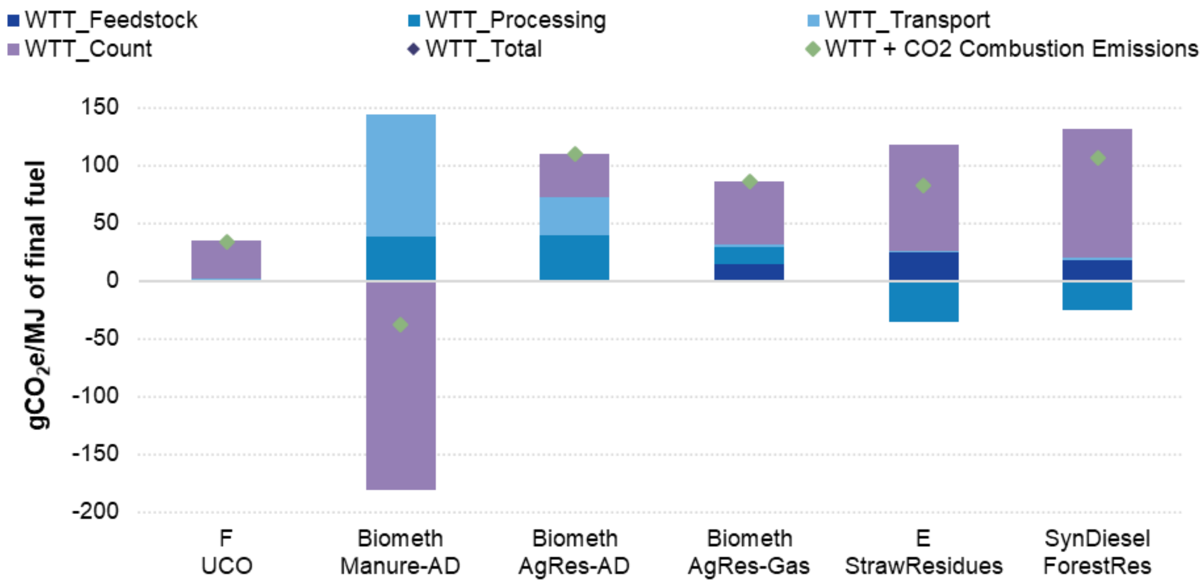
For most secondary feedstocks the counterfactual scenarios currently modelled in the tool (as described in Table 3.10) make a substantial contribution to the WTT environmental impacts of fuels. This is illustrated for fuels made from secondary biogenic feedstocks in Figure 5.38 and for fuels made from secondary fossil feedstocks in Figure 5.39:. It should be emphasised that in this study, only a single counterfactual use is considered for each feedstock, and only a single scenario is considered for the

GWP impact from replacing the feedstock. Therefore, the results reflect one possible scenario for each fuel chain.

Figure 5.38 illustrates trends that are applicable to all of the fuels produced from secondary biogenic feedstocks modelled in this study. All secondary biogenic feedstocks apart from manure are assumed to be diverted from electricity production to liquid fuel production (i.e. their counterfactual use is electricity production). When a biogenic feedstock is diverted from the production of electricity, there is a significant burden added on to the GWP impact of the fuel due to the impact of supplying that electricity by grid electricity instead of from combustion of the biogenic feedstock. Therefore for all feedstocks apart from manure in Figure 5.38 the counterfactual emissions (purple bar) are positive. The impacts from feedstock transport, processing and the counterfactual are magnified when the conversion efficiency from feedstock to fuel is low, which means larger amounts of feedstock are required, as illustrated in Figure 5.38. Here, counterfactual emissions for biomethane produced via gasification of agricultural residues (Biometh AgRes-Gas) are higher than the counterfactual emissions for syndiesel produced from forest residues (SynDieselForestRes), because the latter has a lower feedstock to fuel process efficiency.

The counterfactual use of manure is a direct utilisation (without prior digestion to produce biogas) as a fertiliser on fields. The GWP impacts of diverting manure from this use toward transport fuel production are large and negative (purple bar in Figure 5.38) .This is due to the avoided CH_4 and N_2O emissions from manure storage. When manure is digested anaerobically to produce biogas, the digestate from anaerobic digestion (AD) can still be applied to the field as fertiliser with comparable nutritional value as raw manure, given that nitrogen, phosphorus and potassium remain in the digestate. Therefore there are no additional emissions from having to provide fertiliser to the field in an alternative way. There are still CH_4 and N_2O emissions associated with the storage of digestate, which comprise the majority of the large WTT_Transport impacts for biomethane from manure in Figure 5.38. However these are smaller than the avoided CH_4 emissions from manure storage in the counterfactual case, because of a reduction in volatile solids during digestion (JRC, 2017), hence the net WTT GWP impact is negative for this chain.

Figure 5.38: GWP impact of fuels from secondary biogenic feedstocks (Co-products addressed via substitution | counterfactual impacts included = purple bar)



Note: only represents a sample of fuel chains from secondary biogenic feedstocks

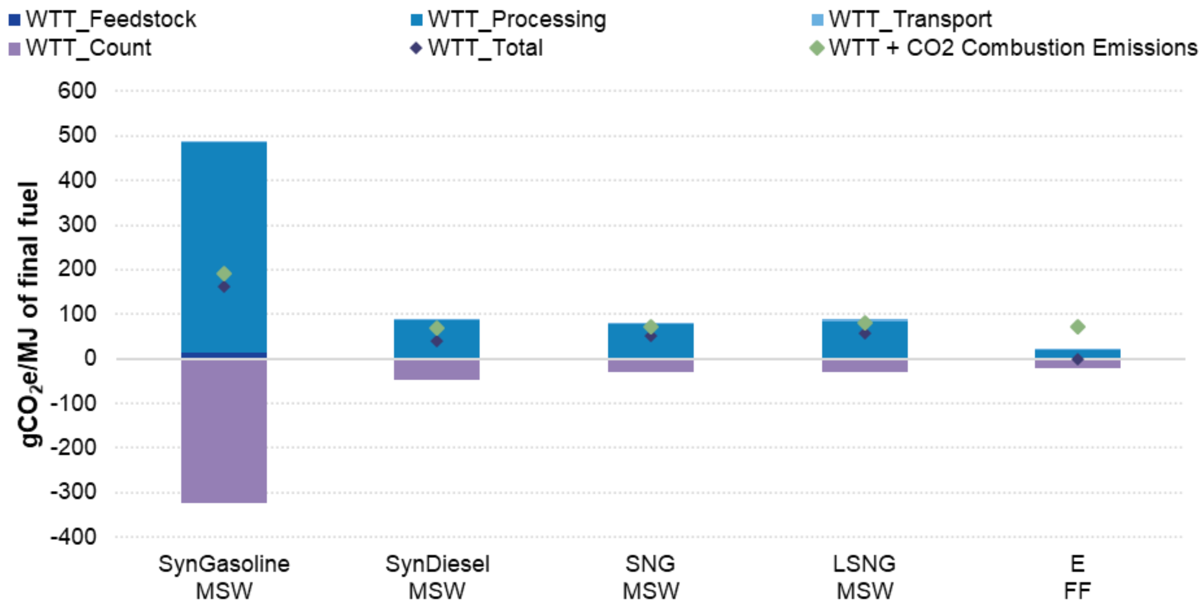
Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

The GWP of fuels produced from secondary fossil feedstock (waste industrial gas) and mixed secondary fossil and secondary biogenic feedstock (MSW) are given in Figure 5.39. Waste industrial gas, which is used for the production of ethanol in the fuel chain labelled E-FF, is the only secondary feedstock within scope of this study which is wholly fossil.

MSW is also a secondary feedstock, but is a mixture of biogenic and fossil material. It is assumed that 61.1% of the carbon in the MSW is biogenic, for consistency with background data on MSW in Ecoinvent. For fuels made from MSW and waste industrial gas the total WTT GWP and the WTT GWP + CO_2 combustion emissions are given in Figure 5.39:. The sum of the stacked bars corresponds to the WTT_Total GWP. Because the method for treating secondary fossil and secondary biogenic feedstocks is the same (see section 3.4.2.3) the results for fuels produced from MSW represent fuel production from the entire mixed fossil and biogenic MSW feedstock.

The counterfactual use of the MSW is assumed to be combustion with electricity generation. The avoided GHG emissions from MSW combustion are 44 gCO_2e/MJ of MSW, which takes into account the fact that 61.1% of the carbon is biogenic, and the emissions from replacing the electricity previously generated from MSW with grid electricity are 28 gCO_2e/MJ of MSW, hence diversion of the feedstock from this existing use results in a reduction in overall GHG emissions. No credit is given for removal of recyclables from the MSW. The negative counterfactual GHG emissions for the MSW fuel chains (purple bar in Figure 5.39:) are partly compensated by emissions of fossil CO_2 (38.9% of total CO_2 emissions) within the processing step and at the point of combustion of the fuel. As for fuels from secondary biogenic feedstocks, the impacts of the counterfactual are magnified when the conversion efficiency is low, hence the net WTT + CO_2 combustion emissions are higher for syngasoline from MSW than for syndiesel from MSW. It should be noted that there were limited data-sources available for modelling fuel produced from MSW (see Appendix A3.12 for more discussion of foreground data).

Figure 5.39: GWP impact of fuels from secondary fossil and mixed fossil and biogenic feedstocks



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

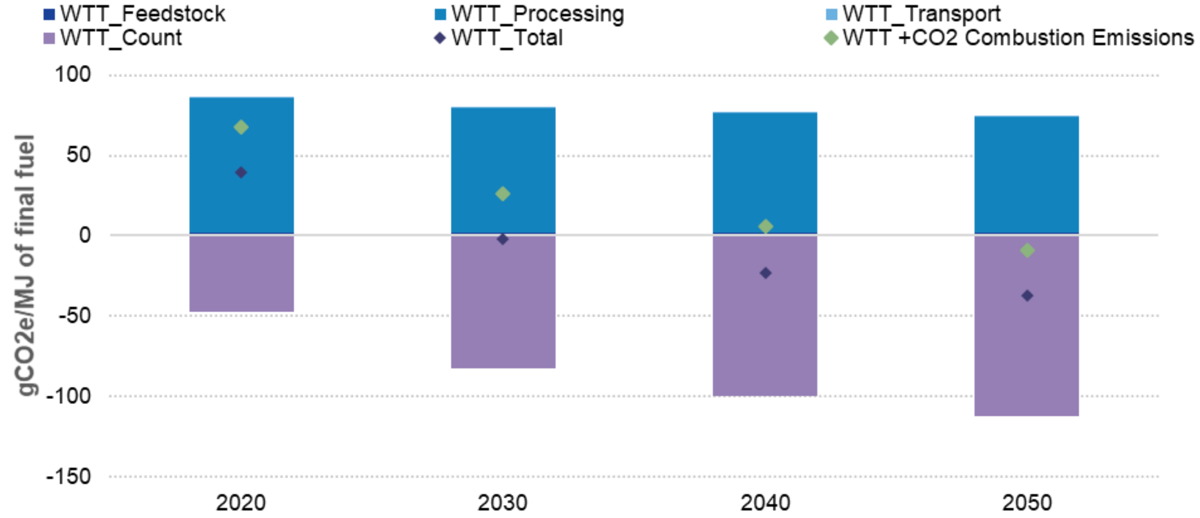
Treating the fossil and biogenic fraction of the MSW consistently in order to calculate the environmental impacts of the total volume of fuel produced from MSW is more representative of the MSW to fuel production process than treating the biogenic and fossil portion of the fuel separately, as sometimes occurs in GHG assessments. If the MSW is mixed, it is not possible to produce fuel from the biogenic portion without also producing fuel from the fossil portion. Therefore considering the environmental impacts of the fuel produced from the total volume of the (mixed) feedstock better reflects the total production process.

For ethanol produced from waste industrial gas (E-FF) the avoided CO_2 emissions from waste industrial gas combustion are equivalent to the CO_2 emissions when the ethanol is burned (the CO_2 combustion emissions, equivalent to the difference between the blue and green markers in Figure 5.39). The purple bar thus represents the sum of these avoided CO_2 emissions from CO combustion, and the positive emissions from replacing the electricity generated with grid electricity. As the grid decarbonises this positive term in the counterfactual emissions (WTT_Count) gets smaller so that the green marker in Figure 5.39 trends towards the top of the blue bar.

Counterfactual environmental impacts are strongly dependent on the use from which the feedstock is diverted and what replaces the feedstock in that original use. As an illustration of this, one can see from Figure 5.40 that as the electricity grid decarbonises over time, the counterfactual emissions of syndiesel produced from MSW get increasingly negative so that the GWP impact eventually become negative. Moreover, in this study the environmental impacts of the average (and not the marginal) way of replacing the secondary feedstock is modelled (see Appendix A3.12.4 for further discussion of this choice). Use of marginal GHG intensities could substantially alter the result, but this was not possible to investigate further within the current study. This clearly illustrates that any attempt to consider the counterfactual impacts of a secondary feedstock should consider the uncertainty in assessing how it is replaced.

A sensitivity analysis for the overall vehicle LCA is provided in later Section 5.5.8, to illustrate the impacts on GWP of including/excluding the counterfactual from the analysis for the fuel blends used.

Figure 5.40: GWP impact of syndiesel produced from MSW (2020 to 2050)



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

5.3.2.3.2 Other lifecycle impacts

Figure 5.41 to Figure 5.44 illustrate the weight of counterfactual scenarios on non-GWP impacts. All examples are taken from chains, for which a counterfactual scenario was modelled to account for the use of secondary feedstocks. In most cases and for most of the fuel chains used in these examples, scores are generally lower without counterfactuals than with counterfactuals. This means that in all cases, the impacts from avoided counterfactuals are offset by the impacts from replacing the counterfactual use of feedstock, which is in line with what is observed for GWP (Figure 5.24). Biomethane from manure was not used here, given that the avoided counterfactual was only modelled for CH_4 and N_2O, which only affect GWP scores. Therefore, no difference would be seen on non-GWP impacts. HTP impacts do not change significantly between scenarios with and without counterfactuals, which is explained by the very low HTP score of the grid electricity used to replace the avoided electricity production out of residues.

Figure 5.41: Effect of counterfactual scenarios on non-GWP impacts (Ethanol from Forest Residues)

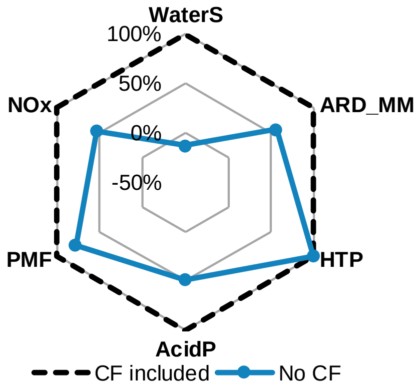


Figure 5.42: Effect of counterfactual scenarios on non-GWP impacts (UCOME)

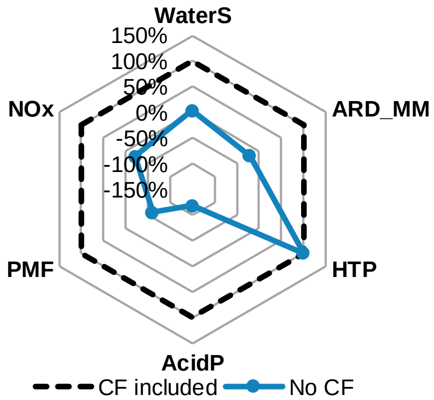


Figure 5.43: Effect of counterfactual scenarios on non-GWP impacts (SNG from MSW)

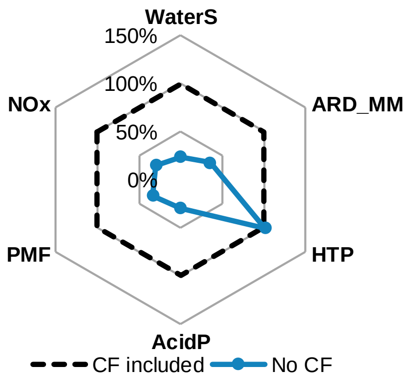
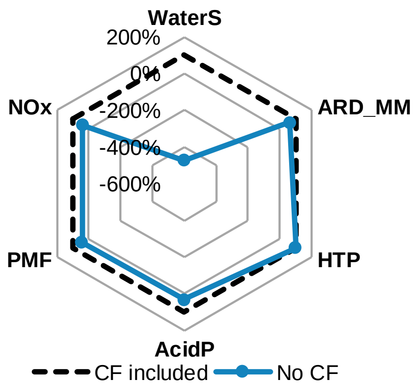


Figure 5.44: Effect of counterfactual scenarios on non-GWP impacts (Syndiesel from Ag. Residues)



5.3.2.3.3 Synthesis

The introduction of counterfactual environmental impacts for secondary fossil and secondary biogenic feedstocks was a novel aspect of this study, and several conclusions can be drawn about the use of this approach:

- Diverting secondary feedstocks from existing productive uses into liquid fuel production can result in significant environmental impacts if that feedstock is diverted from an existing use, and that existing need must continue to be supplied through other processes. This will add to the environmental burden of the fuel (with the possible exception of HTP, should the above results be confirmed over a wider range of fuel chains and counterfactual scenarios). However, the size of that environmental impact is dependent on what the existing use of the feedstock is, and what it is replaced by.
- There may be many possible existing uses of feedstock and for each existing use many different products with which it may be replaced. The current results only represent one possible scenario. For example in this study the diversion of forestry residues from power production is modelled, but this feedstock could be diverted from combustion for heat generation, or may not be used at all, which is the case today for several types of agricultural or forestry residues. Results including counterfactual environmental impacts should therefore not be interpreted as being generally representative of that feedstock or fuel chain, but rather as a "worst case" scenario in which feedstock supply would be limited and any additional unit of biofuel produced

out of it would trigger market-mediated effects. Understanding the existing use of each feedstock is likely to be very specific to the exact nature of the feedstock, time and place at which it is produced; and the product or energy source with which the secondary feedstock is replaced (for example whether average or marginal replacement is modelled). This complexity is an important challenge when practically implementing a consequential LCA approach over such a broad range of fuel chains, with a large number of possible counterfactual scenarios. Additional research is therefore required to define and evaluate counterfactual scenarios more accurately, and generate default values, which could be used in future fuel LCAs implementing a consequential approach.

- The current method of GHG assessment in the RED II where secondary feedstocks have zero GHG emissions until the first point of collection is only valid in the case that they are truly wastes and are not being diverted from an existing productive use. This study shows that where feedstocks are being diverted from an existing use, counterfactual environmental impacts could be many times higher than those from processing alone.
- The following approaches could be implemented to minimise the risk of adverse environmental impacts from the use of secondary feedstocks for fuel production:
  - Including counterfactual environmental impacts in the calculation of GHG emissions for a particular fuel is one way to do this, although this would require careful definition of what the counterfactual use is and what is used to replace the feedstock when it is diverted to liquid fuel production.
  - Counterfactual environmental impacts could be used to identify secondary feedstocks which may be at risk of creating indirect impacts if supply becomes constrained and they are diverted from particular existing uses. These feedstocks could then be subject to tighter scrutiny to minimise the risk of indirect impacts.

Alternatively, all feedstocks could be considered to be co-products of the primary production process so that even feedstocks commonly considered to be ‘residues’ (i.e. those classified as ‘secondary’ feedstocks within this study) must take some environmental burden from the primary production process in which they are produced. This approach was not investigated within this study but could be the subject of future work.

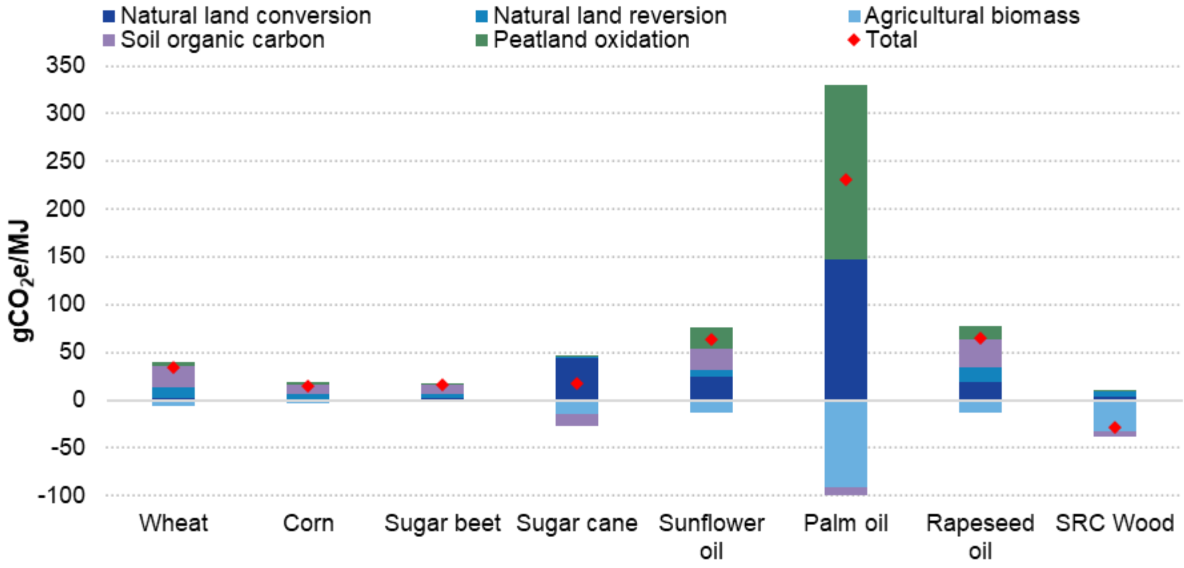
5.3.2.4 Land-Use Change for primary biogenic fuels

In this study, impacts from land-use change are limited to GHG emissions. The inclusion of land-use change GHG emissions in the inventory for feedstock cultivation is a major difference between this study and current policies. While the magnitude of indirect land-use change remains a controversial issue, the importance of considering, not only direct land-use change, but also indirect land-use change was acknowledged as a necessity by a majority of stakeholders. Results from the GLOBIOM model were considered as appropriate.

As expected, adding LUC takes the GWP of primary biogenic fuels to a much higher level than the values found in RED II or analysis by the JEC (Figure 5.13:). When removing LUC values (or when adding the iLUC factors to the RED II values), the results tend to be in the same range. A breakdown of the LUC emissions is included in Figure 5.45. It should be noted that the use of substitution approach does not impact LUC emissions.

One important limitation comes from the short amortization period for the LUC emissions used in this study (Valin, et al., 2015), which is set at 20 years Other studies suggest longer amortization periods would be required to take into account the evolution of global land-use dynamics. No sensitivity was conducted on the impact of amortization period, but different sources suggest that a 100-year period would significantly reduce LUC emissions per MJ of final fuels.

Figure 5.45: Breakdown of LUC emissions used in this study



Source: Based on GLOBIOM (Valin, et al., 2015)

Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

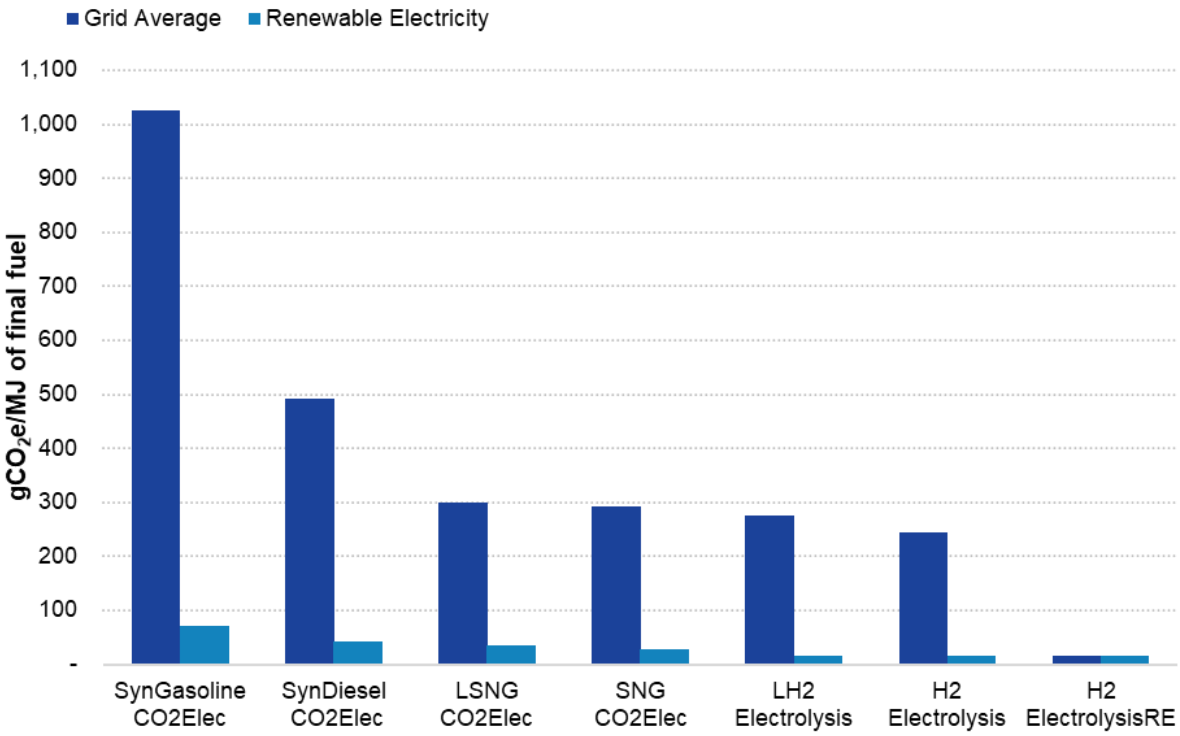
5.3.2.5 Impact of electricity source on LCA results for e-fuels

The main input for e-fuel production is electricity, and therefore, the assumption about the type of electricity supplied to the process (e.g. grid average, renewables only etc.) is significant in determining the overall impacts of the produced e-fuel. It is possible to run scenarios in the tool, where all e-fuels are produced from different types of electricity (renewables or grid average).

5.3.2.5.1 Global Warming Potential

Figure 5.46 highlights the importance of the assumed electricity source on the overall GHG impacts of an e-fuel. It should be noted that the electricity modelled in this study (see Section 5.2) includes the impacts of capital goods so that renewable electricity does not have a zero GWP impact as is assumed e.g. in the RED. The GWP impact of renewable electricity is modelled to be 6.41 gCO_2e/MJ in 2020 and 6.68 gCO_2e/MJ by 2050 – this is because in later periods there is a higher proportion of renewable electricity with more significant capital goods (plant) impacts, such as solar PV. Considering only hydrogen production, excluding any transport and distribution, this leads to an impact between 10.3-10.7 gCO_2e/MJ of produced hydrogen. For some fuels, particularly those such as syngasoline with a relatively low process efficiency, GWP of the delivered fuel can therefore be relatively high even when renewable electricity is used.

Figure 5.46: GWP impact of producing e-fuels from baseline grid average (dark blue) and baseline renewable electricity (light blue)

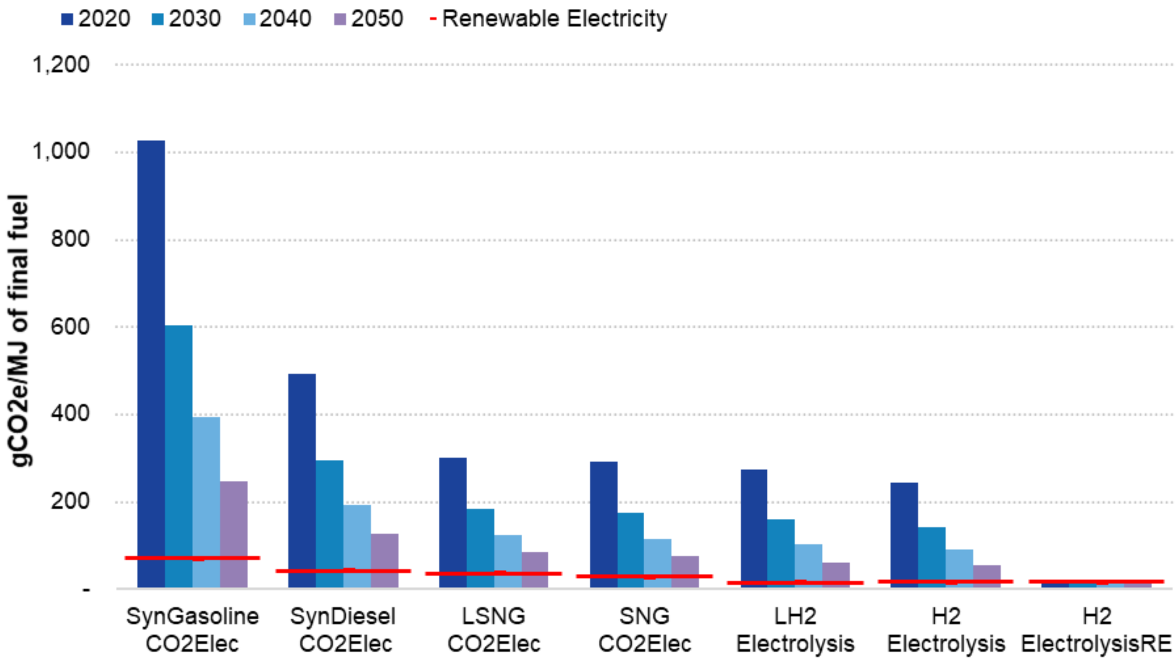


Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

Figure 5.47 illustrates the difference in GWP impact between producing e-fuels with renewable electricity (red line) and producing them with grid average electricity under the Baseline scenario. The GWP impact of producing e-fuels with grid average electricity decreases between 2020 and 2050, due to the strong decarbonisation of the generation mix. However, the total GHG impact of these e-fuels is still greater than if only renewable electricity were used in the production step. This is because even in 2050, the average GWP impact of the grid is 27.02 gCO_2e/MJ in the Baseline scenario, more than triple that of renewable electricity[24]. This confirms the relevance of understanding the situations (grid composition and management) in which e-fuel production would become meaningful. Assuring use of renewable or very low-carbon electricity is therefore key in achieving environmental benefits from the use of e-fuels.

[24] In the Tech1.5 Scenario, the GWP impact of grid average emissions is 3.33 gCO_2e/MJ, which is below the renewable electricity impact, due to the inclusion of biomass plant with carbon capture and storage in the grid average.

Figure 5.47: GWP impact of producing e-fuels from 2020 to 2050 using baseline average grid electricity (columns) compared to using baseline renewable electricity from 2020 (red line)



Notes: the fossil fuel comparator is 94gCO_2eq/MJ in FQD and RED2 (European Union, 2018)

5.3.2.5.2 Other lifecycle impacts

Non-GWP impacts of e-fuels are illustrated in Figure 5.48 to Figure 5.53 below. Results are remarkably homogenous across the different e-fuels modelled, where most impacts used in this example (water scarcity, NOx, PMF and acidification) appear lower when using renewable electricity, than grid electricity. Those impact categories are generally related to the emissions in the air, which are higher when fossil fuels are combusted in plants (e.g. coal or natural gas). The lower water scarcity score may be explained by the large amounts of water used in the cooling process of nuclear or thermal plants, but this aspect would require additional investigation.

Higher impact on abiotic resource depletion (ARD_MM) in renewables can be explained by the significant need for metals and minerals in wind turbines and solar panels on a per MJ basis, compared to non-renewable power production. In addition, the utilisation rate and lifespan of renewable installations, compared to thermal or nuclear power plants may further amplify this trend.

HTP impacts show limited variations (around 10%) between renewables and grid electricity. In general, HTP scores are relatively low in electricity production, regardless of production modes. This is due to lack of reliable HTP data in electricity, these results shall be taken with caution and would require additional research.

Figure 5.48: Effect of electricity production on non-GWP impacts (Syngasoline-CO2Elec)

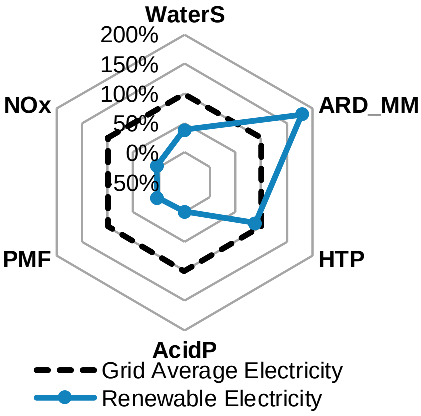


Figure 5.49: Effect of electricity production on non-GWP impacts (Syndiesel-CO2Elec)

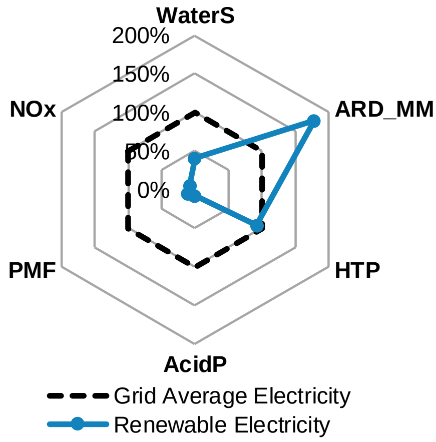


Figure 5.50: Effect of electricity production on non-GWP impacts (LSNG-CO2Elec)

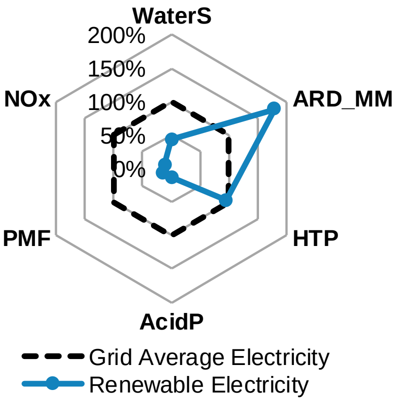


Figure 5.51: Effect of electricity production on non-GWP impacts (SNG-CO2Elec)

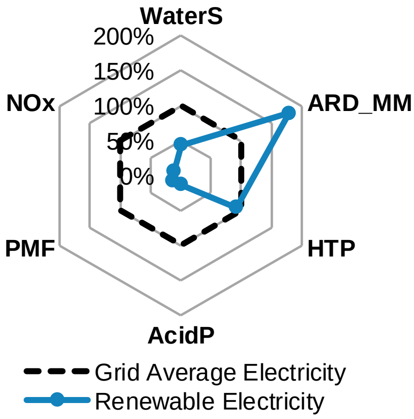


Figure 5.52: Effect of electricity production on non-GWP impacts (LH2-Electrolysis)

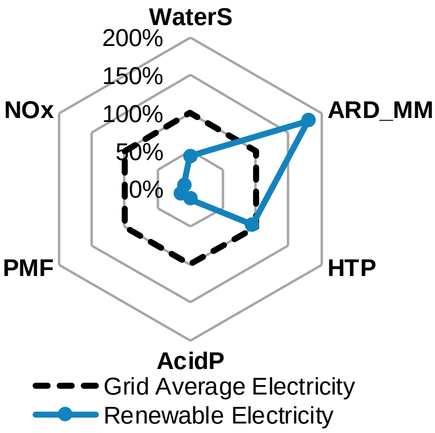
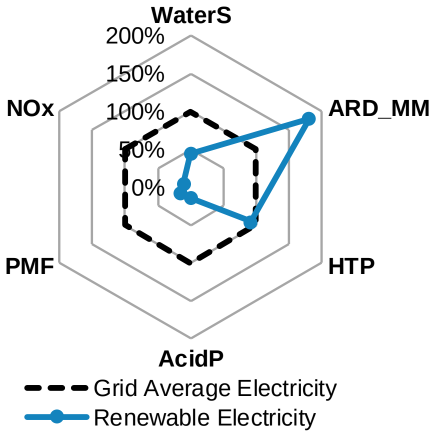


Figure 5.53: Effect of electricity production on non-GWP impacts (H2-Electrolysis)



5.3.2.6 Crude refining: Modelling results (primary fossil fuels)

As stakeholders expressed a strong desire to understand how results for primary fossil fuels derived from crude oil (gasoline, diesel and LPG) compared to other publicly available sources, it was agreed to include a comparison to JEC (2018), particularly as those results are based on (CONCAWE, 2017) which is widely accepted across the refining industry. As the CONCAWE model does not provide non-GWP impacts, a comparison is only possible for GWP impacts, and this is described in the following sections. Emissions from the extraction and refining of crude oil in this study come from the ifeu refinery model

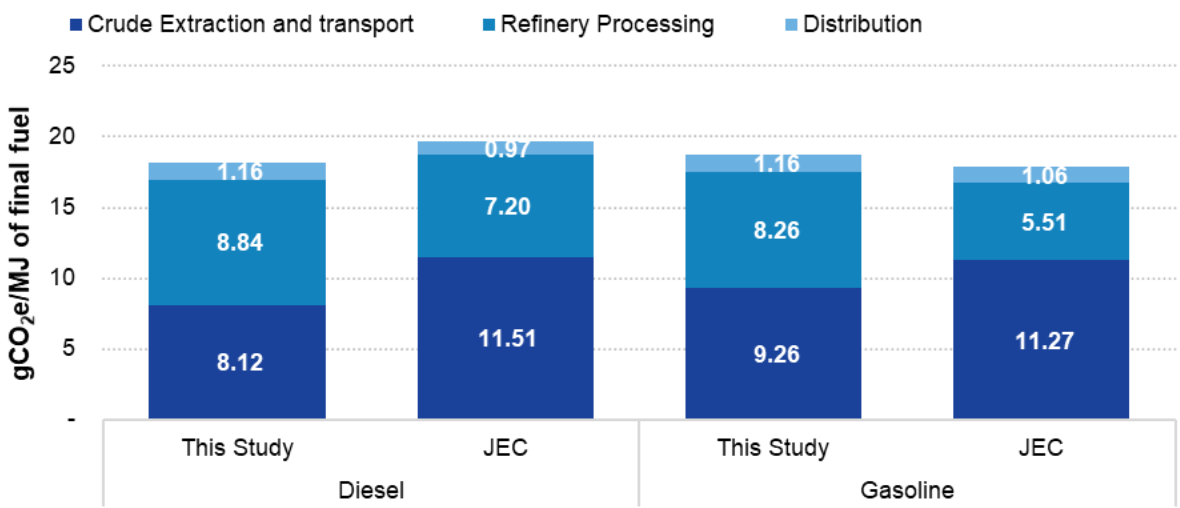
5.3.2.6.1 Diesel and Gasoline

Figure 5.54 compares the WTT GWP impacts calculated in this study for diesel and gasoline against those given in JEC (2018). The following conclusions can be drawn:

- Overall WtT results are comparable; JEC results are marginally higher for diesel (8%), and marginally lower for gasoline (5%); while the GWP impact of refining is lower in JEC, this is offset by a higher GWP impact for crude oil extraction and transport of crude in JEC compared to this study
- Considering the refining life-cycle stage, the ifeu model gives higher GWP impacts for both diesel and gasoline compared to the CONCAWE model (JEC 2018). The biggest difference lies in ifeu model's refining impact for gasoline, which is nearly 3 gCO_2e/MJ higher than the CONCAWE model.

A more in-depth analysis (which is outside the scope of this work) is necessary to explain the differences in the refining step in detail. However, it is likely to be a combination of both differences in input data assumptions (e.g. refinery process unit capacities, assumed energy consumption per unit throughput of these process units), fundamental methodological differences including the allocation method (as described earlier) and other choices such as the impact assessment methodology. Regarding the methodological differences, for each co-product, the ifeu model tracks the material flow along the process chains in the refinery and carries out an allocation based on energy content at process level. Therefore, for the ifeu model, it is understandable that diesel and gasoline have similar impacts as these fuels have similar calorific values. The slightly higher impact for diesel could be explained by the emissions associated with hydrocracking and the deep desulphurisation of diesel.

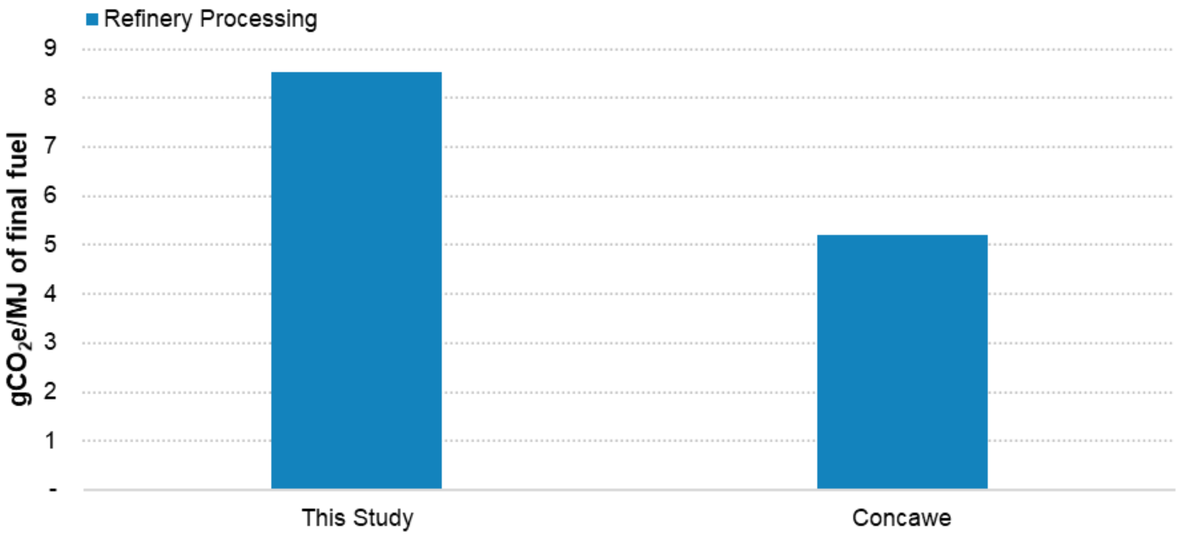
Figure 5.54: Comparison of WTT GWP impacts for diesel and gasoline in this study and JEC (2018)



5.3.2.6.2 LPG

In JEC 2018, the LPG fuel chain, which is modelled, assumes that the LPG is produced as a co-product of natural gas production at a remote field. Therefore, the WtT data for LPG in JEC 2018 is not comparable to that for LPG in this study, where it is assumed that LPG is a co-product of crude oil refining. It is therefore only possible to compare the GWP impact of the refining step in this study with the results given by CONCAWE (CONCAWE, 2017), as shown in Figure 5.55. It can be seen that the refinery life-cycle stage GWP impact given by the ifeu model which is used in this study is 64% higher than that given by CONCAWE. Again, this difference is likely to be due to differences in both input data and methodology, but the further investigation required to determine the exact reasons is beyond the scope of this study.

Figure 5.55: Comparison of WTT GWP impacts from refinery processing for LPG in this study and CONCAWE



5.3.2.7 Natural gas fuel chains

For the natural gas-based chains, it is the choice of foreground data, rather than methodological choices that drives differences (or similarities) in results when compared to other sources such as JEC (2018). Whilst understanding the impact of foreground data choice on results was not the focus of the study, it is still somewhat useful to understand in order to know whether foreground data may need to be investigated further for future work. To achieve this, it is first important to understand the data used for natural gas extraction and processing, for both conventional natural gas and non-conventional natural gas (shale gas).

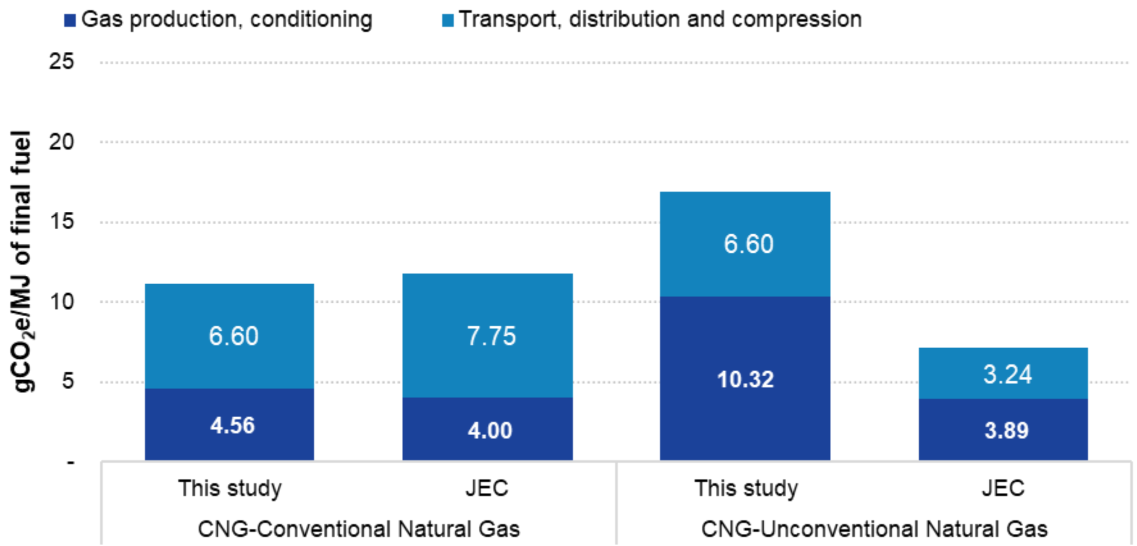
For conventional natural gas Ecoinvent datasets for natural gas production in Russia, Algeria and Germany were used. A weighted average data set was constructed, based on the gas mix as reported from NGVA report (Greenhouse Gas Intensity of Natural Gas, 2017), where Germany was used to represent production in other EU countries, and Algeria represents non-EU countries excluding Russia[25]. GREET was used for non-conventional natural gas as this data is not available in the Ecoinvent dataset. It is important to note that GREET uses data from North American shale gas production.

5.3.2.7.1 CNG

For CNG from conventional natural gas, Figure 5.56 shows that there is good alignment between this study and JEC 2018, both for the gas production and conditioning step and the transport, distribution and compression step. In this study, the downstream transportation, storage and distribution of the CNG produced is taken from Ecoinvent, and this shows that there is good alignment between the Ecoinvent dataset and values used by JEC.

[25] **This approach was necessary as Ecoinvent data sets were not available for gas production in other countries supplying the EU**

Figure 5.56:Comparison of WTT GWP impacts of CNG from conventional and non-conventional natural gas



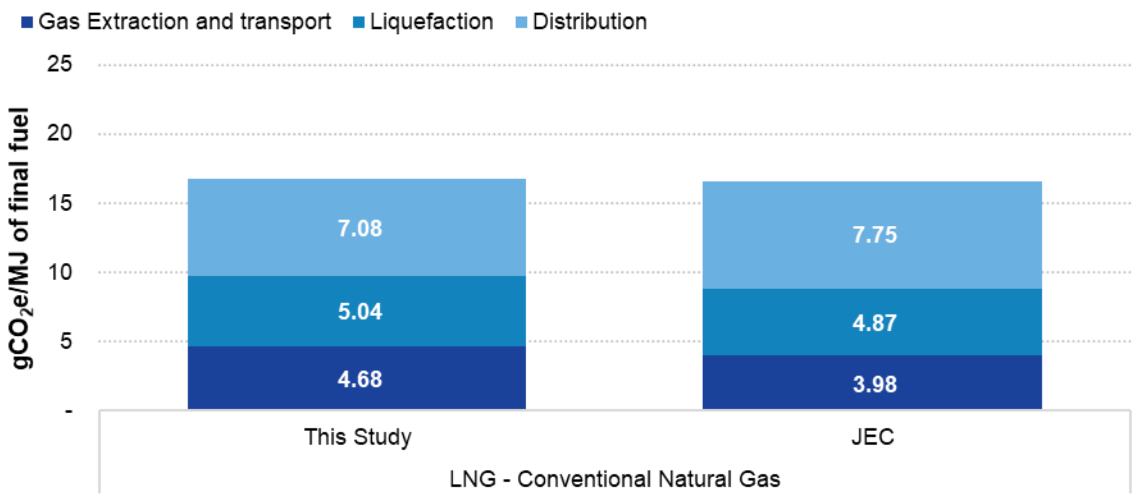
For non-conventional natural gas based CNG, it is evident that results from this study and from JEC differ significantly, primarily due to differing assumptions in the foreground datasets. As discussed above, this study uses North American Shale Gas from GREET, whereas the JEC results in Figure 5.56 are based on an EU shale gas dataset. As can be seen, the GWP impact for this step is significantly higher when using GREET data. It is beyond the scope of this study to look into the details of the exact drivers behind these differences, but it is likely a combination of both input data and methodological differences. It is worth noting that given the North American shale gas industry is far more mature than that of the EU, it is possible that GREET could have a wider range of industry data to derive its results from.

5.3.2.7.2 LNG

For LNG from conventional natural gas, it can be seen from Figure 5.57 that the results from this study show strong agreement with those from JEC. Given that in this study, JEC data was used to model liquefaction of natural gas as well as the downstream transportation, storage and distribution of LNG, this result is unsurprising.

JEC (2018) does not provide results for LNG production for non-conventional natural gas, and thus a comparison was not possible.

Figure 5.57: Comparison of WTT GWP impact for LNG from conventional natural gas in Module 3 and JEC (2018)



5.3.2.7.3 Transport, distribution and compression

This study uses the same assumptions for both conventional and non-conventional natural gas for this step, based on the assumption that the natural gas will be transported from the production source to the distribution network via a long-distance pipeline. However, in the JEC data for CNG from shale gas, it is assumed that there is no need for long distance transport (gas is immediately fed to the European high pressure network), which likely explains why the GWP impact is around 50% of the value in this study.

5.4 Results for the overall vehicle LCA

This section provides a summary of the key results from the overall Vehicle LCA, including all stages within the boundary for the analysis – i.e. covering the vehicle manufacturing stage, the vehicle operation stage, and end-of-life/disposal stage; These results are obtained by using WTT inputs based on energy allocation (all fuels), without impacts from counterfactuals (secondary fossil and biogenic fuels) and without land-use change (primary biogenic fuels). Results are generally presented in terms of impacts per vehicle-km for all modes, except for rigid and articulated lorries, where results are presented on a per tonne-km basis instead to better represent the utility of these vehicles.

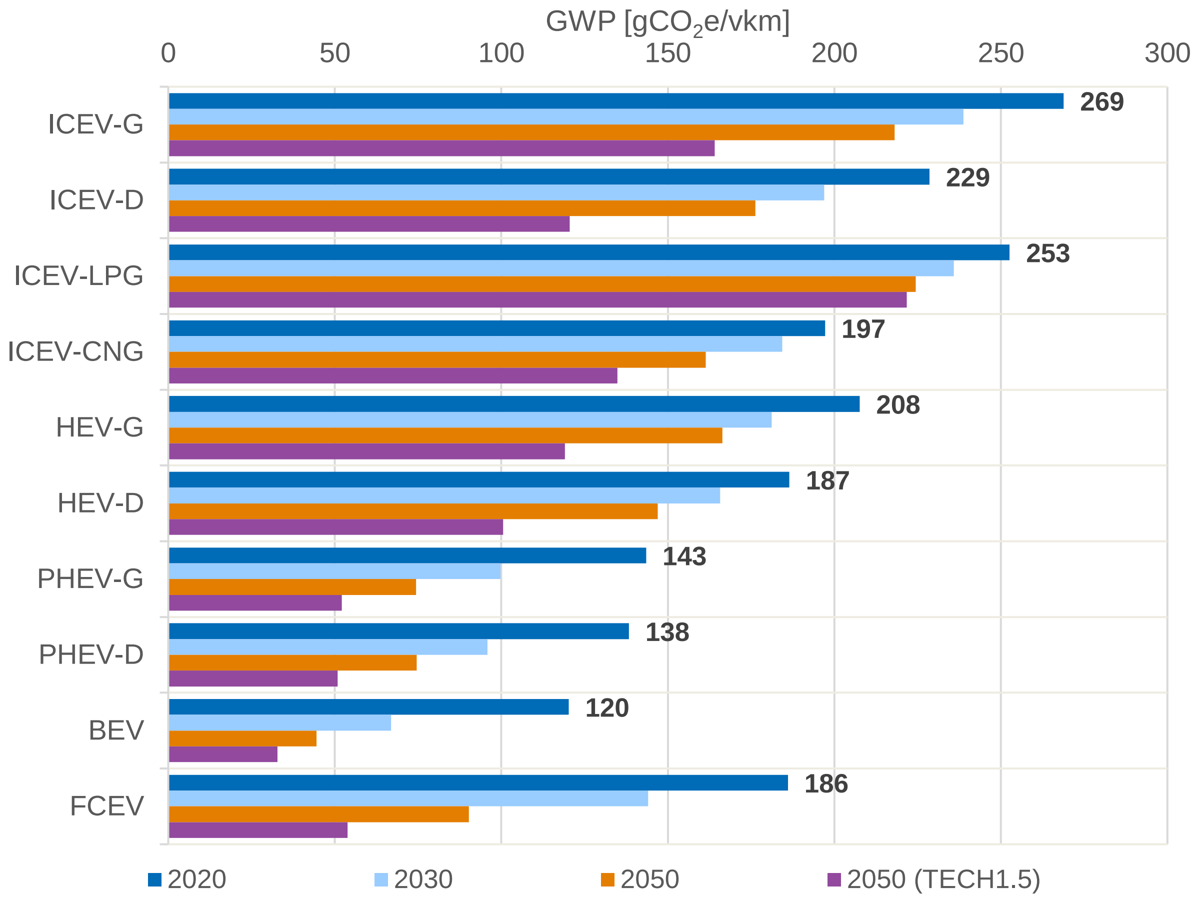
Earlier Section 4.7 provided a summary of the key background data assumptions (with more detail included in Appendix A4 also). This also included a summary of the assumed fuel blends/production mix (Figure 4.11) and the resulting average fuel blend outputs for the GWP (Figure 4.12). Further information is also available on the results in Appendix A5 of this report, and in the accompanying results database files which are explorable in the provided 'Vehicle LCA Results Viewer'.

5.4.1 Lower-medium passenger cars

5.4.1.1 Lifecycle GHG emissions

Figure 5.58 provides a summary of the overall LCA results for Lower Medium Cars for the GWP impact category, with a breakdown between different lifecycle stages given in Figure 5.59. The results show that electrified powertrains have a lower GWP impact than conventional equivalents, that this benefit increases with an increasing degree of electrification and also that benefits increase over time. The latter is due to the decarbonisation of the grid electricity mix used to operate the vehicles. Impacts for PHEVs and BEVs in 2020 are relatively similar, but diverge significantly in the future due to a combination of reduced impacts from battery manufacturing and increased decarbonisation of grid electricity used to operate the vehicles (see Figure 5.59).

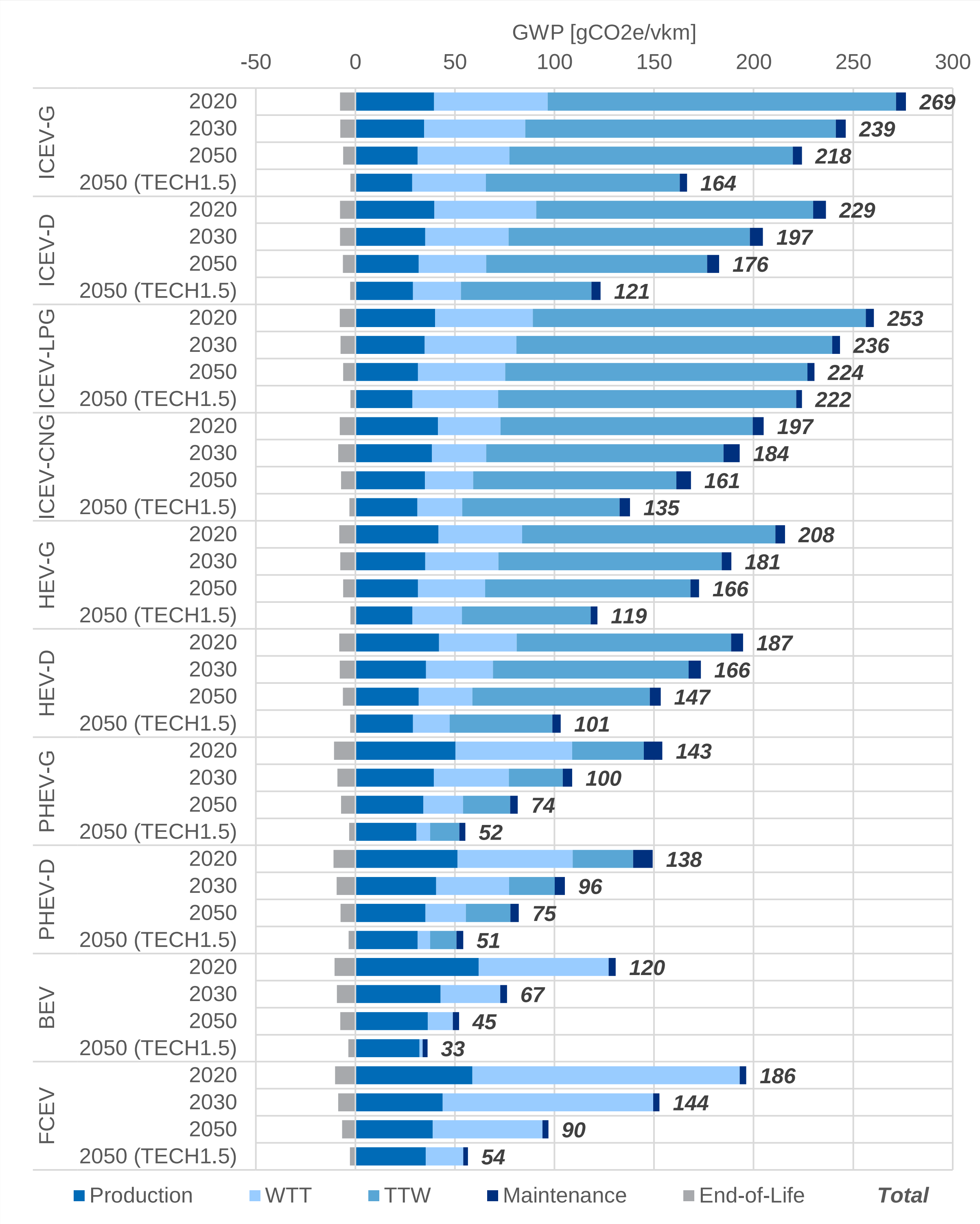
Figure 5.58: Summary of overall lifecycle GWP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020, 2030 and 2050; Tech1.5 scenario for 2050)



Notes: Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery has a 58 kWh, a 300km range, and with average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs, based on the battery lifetime methodology implemented factoring in cycle life, kWh capacity and lifetime vkm.

Impacts for FCEVs are similar to those of CNG vehicles and HEVs in the 2020 time-horizon, assuming operation on hydrogen produced by reforming of natural gas (SMR, steam methane reforming), which has lower impacts than hydrogen produced from grid average electricity over the 15-year operational life of the vehicles. The results show impacts for FCEVs that are around 50% or more higher than for equivalent BEVs across the timeseries. This is due to the lower overall efficiency of the full energy chain (including vehicle efficiency) for hydrogen produced from electricity (versus using it directly in a PHEV or BEV). Much higher shares of renewable/low carbon electricity (versus grid average) are required for hydrogen production via electrolysis before benefits approach those of BEVs running on grid average electricity. Operation in 2050 for FCEVs in the Tech1.5 scenario assumes 50:50 production using electrolysis and SMR+CCS (SMR with carbon capture and storage).

Figure 5.59: Summary of breakdown of overall lifecycle GWP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020, 2030 and 2050, Tech1.5 for 2050)



Notes: Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

The results show that whilst vehicle manufacturing impacts are significantly larger for BEVs than for FCEVs in 2020, they may be broadly similar by 2050 due to a combination of assumed improvements in battery energy density and reduced impacts resulting from electricity used in battery manufacturing.

The GWP impacts of natural gas fuelled vehicles (ICEV-CNG) are significantly lower than those of conventional gasoline or diesel-fuelled vehicles, achieving similar benefits to full hybrid electric vehicles (HEV) and FCEVs in 2020. These benefits are due to a combination of lower impacts per MJ energy for both the WTT and TTW components of the CNG fuel chain, compared to conventional liquid fuels, as illustrated in Figure 5.59.

Impacts reduce at a faster rate over time for the Tech1.5 scenario, versus the baseline scenario assumptions due to a combination of improved vehicle efficiency, reduced impacts from production of materials and vehicles, and further decarbonisation of the energy carriers used for vehicle operation (particularly electricity) (also discussed in earlier Sections 5.2 and 5.3).

For vehicle production there are significantly higher impacts for the production of PHEVs, BEVs and FCEVs compared to conventional ICEV and hybrid (HEV) vehicles. These differences are the highest in 2020, with BEVs resulting in around 66% higher impacts from manufacturing – with these impacts representing over half of the overall lifetime impacts from BEVs – see also Figure 5.60. This differential is significantly lower than in some previous studies, including some of Ricardo's previous analysis, which have shown a difference in excess of 100% in some cases. However, our new analysis for this project has taken into account significantly improved methods for calculating battery impacts including more up-to-date datasets on battery characterisation and manufacturing energy consumption based on (ANL, 2018). Our input assumptions and results are also broadly in line with other recent analyses of such impacts from (IVL, 2019).

The following Figure 5.60 provides a comparison of the breakdown of GWP impacts for lower medium cars between different vehicle systems for a number of xEV powertrains, and how this is projected to change over time (particularly as battery and fuel cell manufacturing decarbonises). For FCEVs, the majority of the impacts for energy storage are due to the high-pressure (700 bar) compressed hydrogen storage tank, which is made mostly from carbon-fibre reinforced plastic. This material has an extremely high production impact, and with only part of its manufacturing impacts due to electricity consumption, it does not decarbonise at the same rate as some other materials. Should a new and improved/lower impact hydrogen storage technology be introduced in the future, this could further reduce the manufacturing impacts of such powertrains. Since CNG and particularly LPG tanks do not require such high-pressure materials/exotic materials, they only contribute to relatively small increases in the manufacturing impacts of vehicles using these fuels (versus conventional fuel equivalents).

Figure 5.60: Breakdown of GWP impacts for Lower Medium Car for BEV and FCEV powertrains materials and component manufacturing, Baseline scenario

PHEV-G

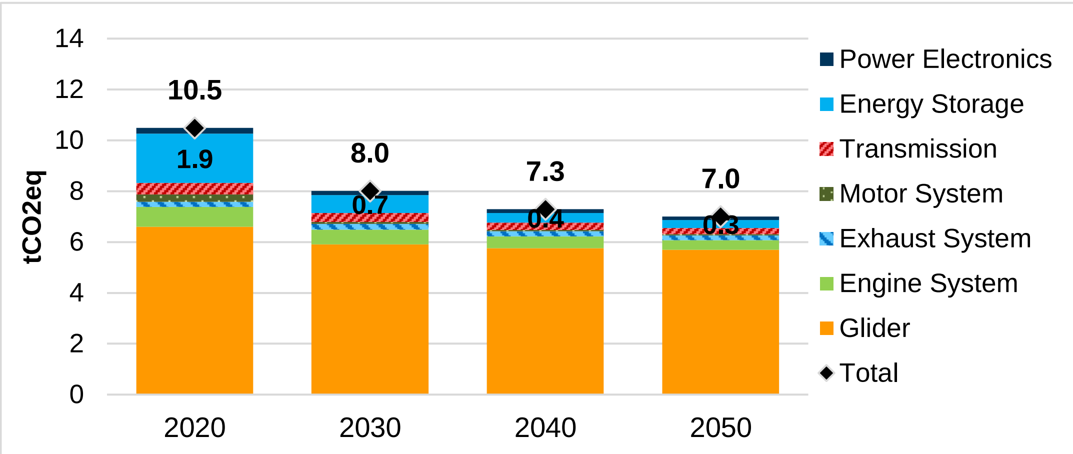
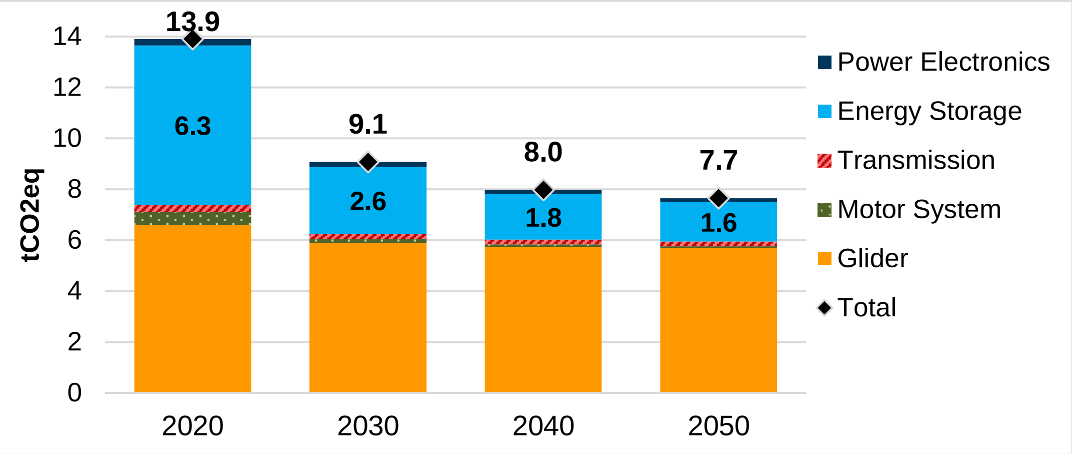
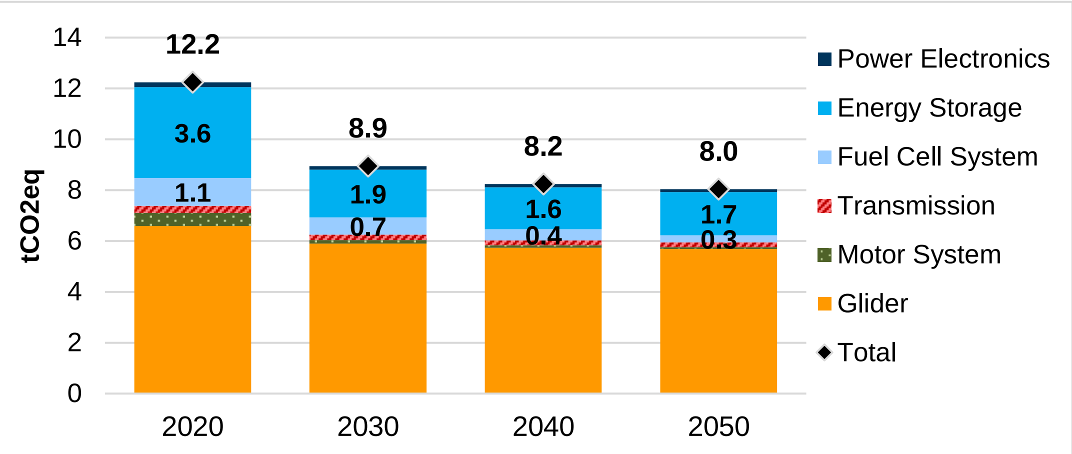


Figure 5.60: Breakdown of GWP impacts for Lower Medium Car for BEV and FCEV powertrains materials and component manufacturing, Baseline scenario





Notes: Impacts from vehicle assembly are not included in the above charts. Energy storage for FCEVs includes a small battery and a 700bar hydrogen storage in a carbon-fibre reinforced plastic pressure vessel.

In terms of the relative importance of materials in the glider for passenger cars (common for all powertrain types), Figure 5.61 provides an illustration of the relative importance of a number of key materials from a total mass and total GWP impacts perspective. This chart illustrates the relatively high impacts of both aluminium and textiles per unit mass. Whilst aluminium is a light-weight structural material that can offset its increased impact through fuel savings, this is not the case for textiles. As noted earlier in Section 5.2, textile manufacturing is highly energy intensive. Actions taken by OEMs to use more sustainably sourced /manufactured textile materials in vehicles are therefore likely to produce notable benefits.

Maintenance impacts, due to replacement parts / consumables (like tyres, oil, etc.) are a relatively small contributor to the overall result shown in Figure 5.59. As the battery is anticipated to last the lifetime of the vehicle in the vast majority of use cases, the impacts for BEVs are estimated to be around half those of diesel ICEVs, due to fewer replacement parts and consumables (i.e. no exhaust replacement, engine oil and AdBlue consumption). Impacts are slightly higher for diesel versus gasoline ICEVs mainly due to the assumptions on AdBlue consumption in aftertreatment systems to control NOx emissions.

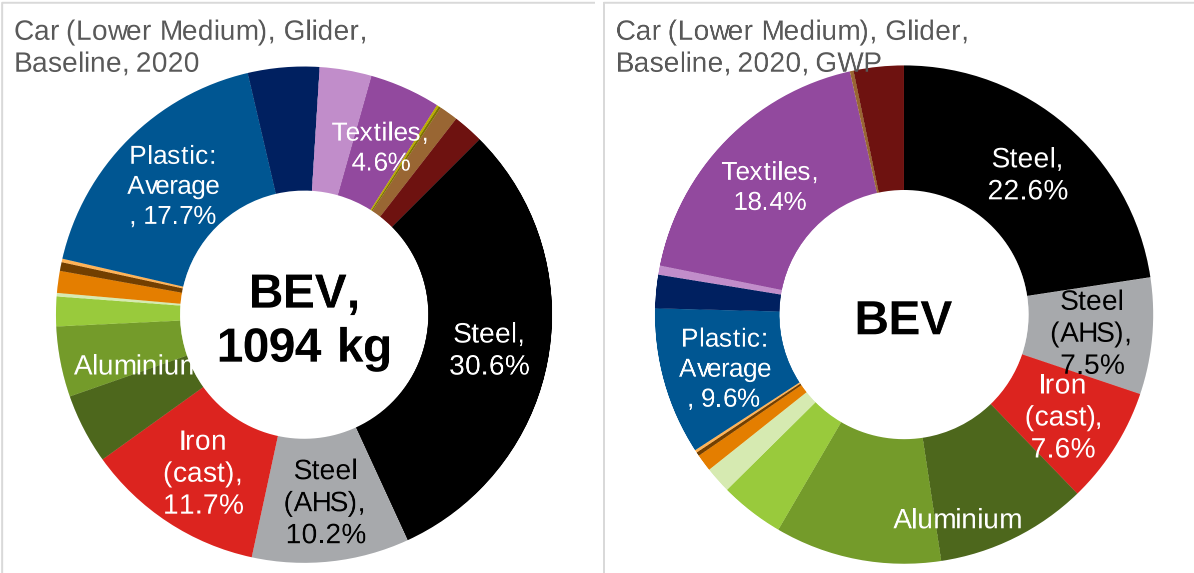
For all powertrain types Figure 5.59 also shows there are net credits/benefits expected due to a combination of end-of-life impacts and credits. These impacts and credits are from vehicle and battery recycling processes, energy recovery and disposal (to landfill) of remaining materials[26]. The net credits amount to around 14-16% of the overall impacts of vehicle production for lower medium cars. This is

[26] In the modelling definitions, input assumptions have been calibrated to ensure that end-of-life (EoL) vehicles are compliant with the overall targets set out for vehicle recyclability and recovery in Directive 2000/53/EC on end-of-life vehicles (European Union, 2000).

much lower than some other studies that have also accounted for EoL recycling credits, for example (ECF, 2017) estimated credits equivalent to around 30% of vehicle and battery manufacturing impacts.

Figure 5.61: Breakdown of (i) mass (kg) and (ii) GWP impacts, for Lower Medium Car materials in the Glider (common to all powertrains types), Baseline scenario

(i) Breakdown by material mass (kg) *Breakdown by material GWP impact*



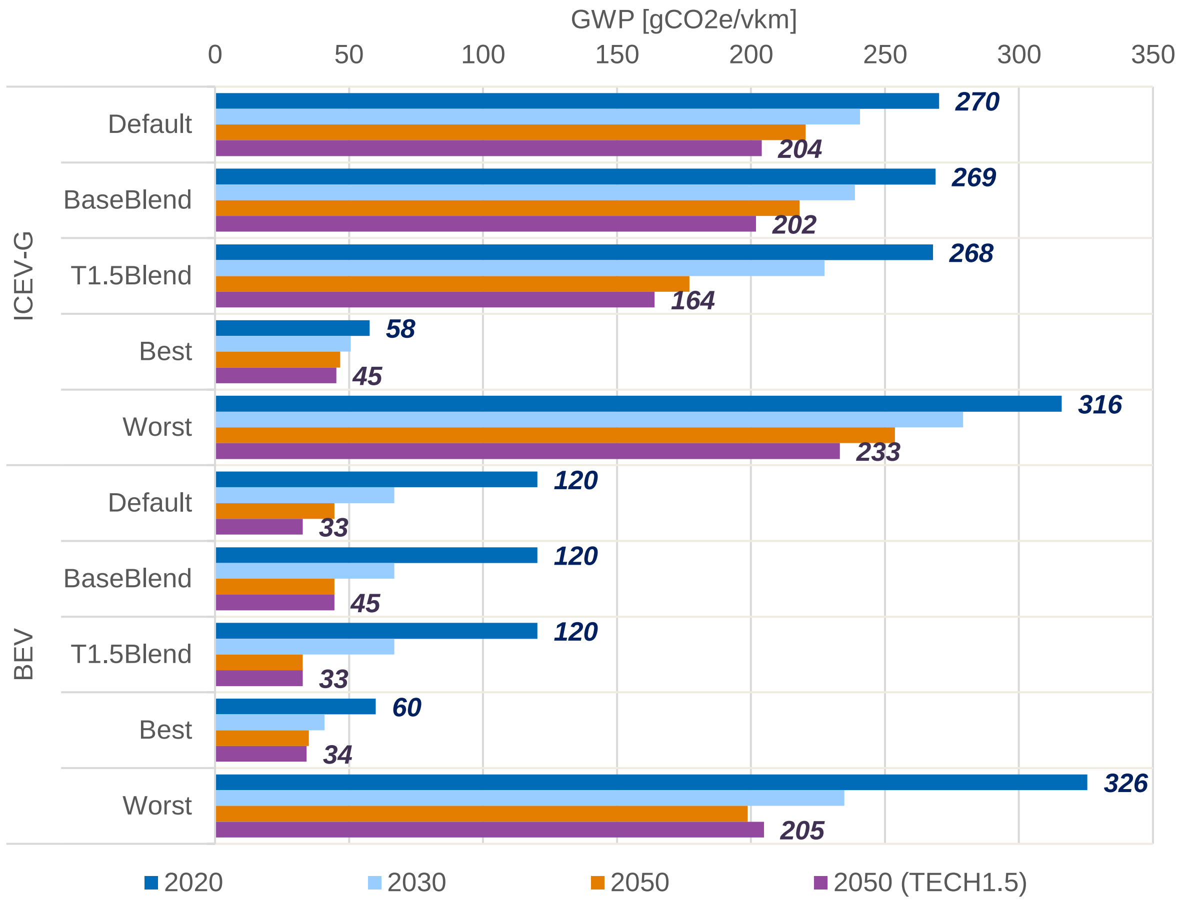
Notes: Other key materials not specifically named in the figures include copper, glass, rubber/elastomer, fluids.

The impact of operational energy consumption is the single largest contributor to overall impacts for most powertrain types currently, though the relative share can vary significantly. Figure 5.62 provide further context for two extremes in this context – conventional gasoline ICEVs and BEVs, showing how the relative performance of these two powertrains is highly influenced by the energy production chain/source. Figure 5.62 provides an illustration of the impacts on the result for different fuel blends, electricity mixes and for the lowest/highest 2020 GWP/ fuel/electricity production chains. For the ICEV-G, the lowest GWP fuel chain is ethanol produced from SRC (short-rotation coppice), whilst the highest GWP fuel chain is ethanol produced from wheat. For electricity generation the lowest GWP chain is taken as the renewable electricity average, and the highest being for coal generation.

Over time, given the widespread trend towards decarbonisation of electricity in the EU, the effects of regional variation in electricity mix become smaller. As a result, the overall GWP impacts from the BEV are also lower in future periods (shown for 2030 in the figure) and the gap in the performance of the BEV vs the ICEV-G increases for all EU Member States. In addition, similar effects are observed for other vehicle types.

It can therefore be concluded that using the EU28 average to assess the impacts of vehicles is likely to hide significant differences in regional electricity mixes that affect the relative performance of powertrains and therefore their relative benefits in different EU Member States. These effects diminish over time as countries converge towards the use of lower carbon intensive sources of energy.

Figure 5.62: Summary of the influence of fuel/electricity chain assumptions on overall lifecycle GWP impacts for Lower Medium Cars for Gasoline ICEV and BEV powertrain types



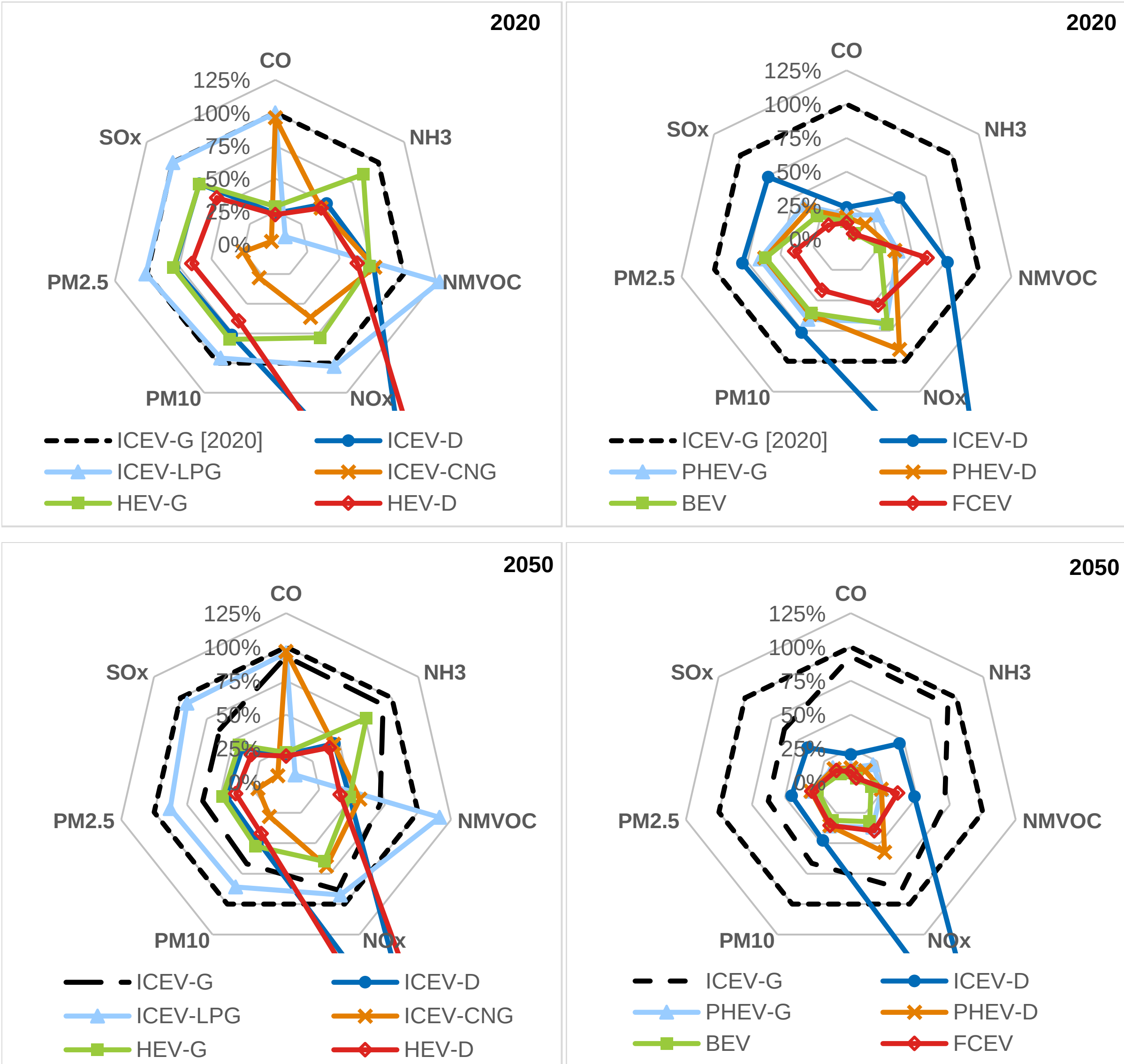
Notes: Results are presented for operational energy consumption based on Baseline scenario for 2020, 2030 and 2050, and Tech1.5 scenario for 2050). 'Default' is assumed to be 100% conventional fossil fuel production chain, grid average electricity for operation of plug-in EVs and hydrogen production via SMR for FCEVs. For ICEV-G: 'Best' = E-SRCWood, 'Worst' = E-Wheat; for BEV: 'Best' = RenewableAv, 'Worst' = Coal generation.

5.4.1.2 Other lifecycle impacts

The following Figure 5.63 provides a summary of the relative lifecycle emissions of air pollutants (CO, NH_3, NMVOC, NOx, PM_{10}, $PM_{2.5}$, SOx) for lower medium cars resulting from the analysis (scaled to a 2020 gasoline ICEV = 100%). Earlier Figure 2.7 in Section 2.2.3.1 provided a summary of the relative contribution of road transport to total EU emissions of these pollutants, where NOx is particularly important (~30% of total EU emissions). However, it should be noted that (a) health impacts from most of these pollutants are highly location-specific (i.e. depending on exposure levels – highest in urban areas) and (b) some of the lifecycle emissions presented here will have occurred outside of the EU (i.e. mainly from fuel and materials production, battery manufacturing), so will not be directly regulated or accounted for within the national/EU inventories. The results show significantly lower lifecycle impacts for xEVs versus liquid/gas fuelled powertrains for all pollutants, compared to conventional gasoline and diesel vehicles. These benefits also increase in future periods. In the majority of cases, the majority of the emissions of individual pollutants is in the fuel production stage (i.e. WTT), except for NOx from diesel vehicles, and for CO from conventional gasoline, LPG and CNG vehicles – where exhaust emissions dominate. However, as noted above, the location of emission is also important when accounting for the relative impacts of different air quality pollutants, and significant proportion of fuel WTT impacts will be expected to occur away from more populated areas.

Figure 5.63: Summary of the relative impacts for Lower Medium Cars for air quality pollutant emissions (CO, NH_3, NMVOC, NOx, PM_{10}, $PM_{2.5}$, SOx) for 2020 and 2050 powertrains.

i. Conventional versus gaseous and hybrid vehicles *ii. Conventional versus xEV powertrain vehicles*



Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. Exhaust (TTW) air pollutant emissions are based on the version of COPERT current at the time this report was prepared, however an update is planned for later in 2020, which may result in changes to the relative performance of some powertrains.

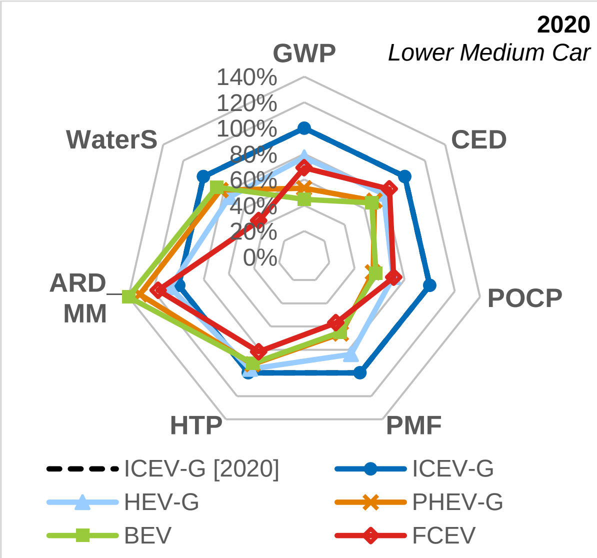
Figure 5.64 provides a summary of the relative performance of a range of increasingly electrified powertrains (scaled to a 2020 gasoline ICEV = 100%). Impacts for diesel ICEVs are significantly higher for both POCP and PMF (as also NOx contributes to secondary PM2.5 formation – see 2.2.3.1). Further information is also provided in Appendix A5.3.1 on the breakdown of the specific impacts for individual powertrain types.

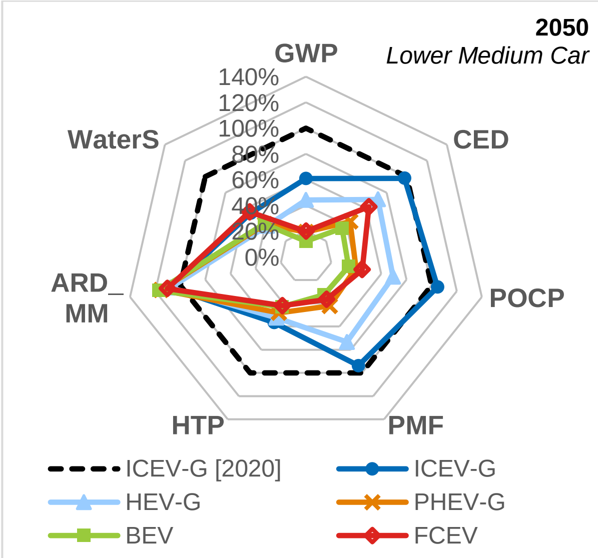
Cumulative Energy Demand (CED):

For CED, the relative breakdown between the different lifecycle stages is similar to that presented in earlier Figure 5.59 for GWP, except all fuel/electricity impacts fall within the WTT component. The overall results for lower medium cars show that CED is significantly reduced/improved for more efficient powertrain types, with the results for 2030 being closer to 2050 values (compared to 2020). The results for most xEVs are similar for 2020, but increasingly diverge in later periods with fully electric vehicles (BEVs) performing the best (around half the CED of conventional ICEVs). The CED performance of CNG-fuelled ICEVs is better than gasoline, diesel or LPG equivalents.

FCEV perform significantly worse than BEV, PHEV after 2020: around 50% more than BEV by 2030, and almost double BEVs by 2050. This differential is due to the net of fuel chain (including an assumed increase in share of electrolysis for hydrogen production) and higher relative vehicle powertrain efficiency for BEV versus FCEVs. This result is particularly important in the context of potential constraints on the availability of renewable / low carbon electricity, where over double the amount of energy would be required to fuel FCEVs versus BEVs.

Figure 5.64: Summary of the relative impacts for Lower Medium Cars for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Tech1.5 Scenario.





Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%.
GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity

Photochemical Ozone Creation Potential (POCP):

For POCP, the relative share of impacts for vehicle production and EoL is greater, with WTT and TTW fuel/electricity impacts relatively significantly smaller component of the total for most powertrains. The exception is for diesel ICEV and HEV, where tailpipe emissions dominate the result. The highest impacts are seen for diesel HEVs, which are based on COPERT real-world emissions factors for these vehicles. The POCP impacts for LPG and CNG vehicles are similar or higher than those for gasoline ICEVs, but lower than those for diesel.

For electricity, conventional fossil generation types have the highest impacts, but these are very small in the context of emissions from vehicle production and tailpipe emissions. xEVs have higher impacts due to the manufacturing of batteries, with BEVs having higher overall impacts than PHEVs and FCEVs in 2020 (but still lower than all the ICEV and HEV powertrains). The POCP impacts for PHEVs, BEVs and FCEVs all reduce significantly in later periods and reach similar levels by 2050; however, the impacts for ICEVs and HEVs do not significantly reduce by 2050.

Particulate Matter Formation (PMF):

For PMF, the direct PM2.5 emissions are similar for all powertrain types, as these are now dominated by high shares of brake, tyre and road-wear, rather than exhaust emissions due to the application of particulate filters in new vehicles. However, there is a significant contribution of NOx to secondary PMF for diesel, which leads to diesel ICEVs and HEVs having the highest overall lifecycle impacts.

As for POCP, the highest impacts are for diesel HEV due to real-world tailpipe emissions factors for NOx based on COPERT speed-emission curves. The lowest lifecycle impacts in 2020 are for CNG-fuelled ICEV, however impacts due to aftertreatment are significantly higher after 2020, which also increases impacts due to 1 anticipated replacement to the exhaust and aftertreatment in the vehicle lifetime. This is due to the higher platinum loading (and lower palladium loading) for NG aftertreatment systems compared to those for gasoline: platinum has a much higher PMF impact factor.

For electricity, conventional fossil generation types have the highest impacts, but PMF impacts are still lower than those for liquid and gaseous fuelled vehicles. Similarly to POCP, xEVs have higher impacts due to the manufacturing of batteries, with similar trends for these and for conventional ICEVs and HEVs.

Human Toxicity Potential (HTP):

The HTP impacts are dominated by the materials used in vehicle and battery manufacturing, which account for between 62% (for gasoline ICEV) to 97% (for BEV) of the total lifetime impacts in 2020. For BEVs, these total impacts are mostly due to the use of copper in the battery anode current collector, with copper use in wiring and the motor contributing to a much smaller extent (<20% of the total). A number of potential battery and motor technologies currently being explored offer the potential to reduce copper use, for example copper current collectors might be replaced with aluminium for certain chemistries being researched (not possible at the moment due to current chemistry restrictions) and copper motor windings might be replaced with aluminium (also with weight benefits).

For conventional powertrains, there are smaller impacts due to fuel production and maintenance (mainly due to exhaust and aftertreatment replacement due to platinum group metal catalyst content). It is worth highlighting that none of the main regulated exhaust tailpipe pollutants contribute to the HTP impact factor, even though they all have established human health respiratory impacts.

As discussed in earlier Section 3.1.5.2, the HTP impact factor is perceived to have a relatively lower level of robustness compared to other impacts, and consequently has a relatively low final weighting factor recommended by JRC (see Table 3.5) (Ceruttin, Sala, & Pant, 2018). Therefore its significance to the overall comparison should not be overstated, however the indicated hotspots nevertheless highlight the potential areas for future improvement.

Abiotic Resource Depletion – Minerals and Metals (ARD_MM):

The ARD_MM impact category is also dominated by impacts due to material use in vehicle and battery production and EoL stages, with the highest impacts for BEVs (around double those of conventional powertrains in 2020). Similarly to HTP impacts, hotspots for xEVs are mainly due to electronic components and copper use in batteries. The use of cobalt, nickel and lithium in Li-ion batteries is a very small percentage of the overall battery mass, and does not meaningfully contribute to this impact category, despite the acknowledged potential future challenges for sourcing such materials to meet potential demands for xEV batteries (Ricardo, 2018), (Ricardo Energy & Environment, 2019).

Overall impacts from the vehicle production phase for all vehicle powertrain types arise predominantly from the use of steel for the glider, and also from electronics and copper in batteries for xEVs. Impacts from vehicle EoL recycling are also positive (rather than credits) for all powertrains except BEV/FCEV in 2020, which appear to arise due to impacts from aluminium recycling based on the underlying background LCI dataset from ecoinvent; however it is unclear why this should be.

Impacts from electricity use are a relatively small component of the total, with these impacts predominantly due to the relatively very high ARD_MM impacts per kWh for solar PV generation (which are much higher than for other generation types) and to a lesser degree due to relatively high ARD_MM impacts for wind and nuclear generation types, which are much higher than other generation.

Water Scarcity (WaterS):

Water scarcity impacts are completely dominated by the fuel/electricity production (WTT) stage (over 90% of all impacts), with the highest impacts for gasoline ICEVs, and the lowest impacts for CNG-fuelled vehicles (~80% lower than gasoline ICEV). Impacts for FCEVs, shown in Figure 5.64 below, increase for FCEV between 2020 and 2050 due to a higher share of hydrogen production by electrolysis in later periods (to ~50% by 2050). Production using 100% electrolysis would lead to substantially higher impacts for FCEVs compared to other powertrain types. However, actual impacts for water scarcity will depend on the source of water used for hydrogen production: for example, where hydrogen production occurs using deionized seawater (rather than freshwater), such impacts will be much lower.

Impacts from electricity production are highest for coal and solar generation types (with a similar magnitude), and lower for other generation types. Perhaps somewhat counter-intuitively, water consumption appears to be lower for many biofuel chains, compared to fossil equivalents. However, recent survey work by (ANL, 2019), has shown that biofuel producers have also been making significant improvements to water consumption in recent years.

Other impact categories:

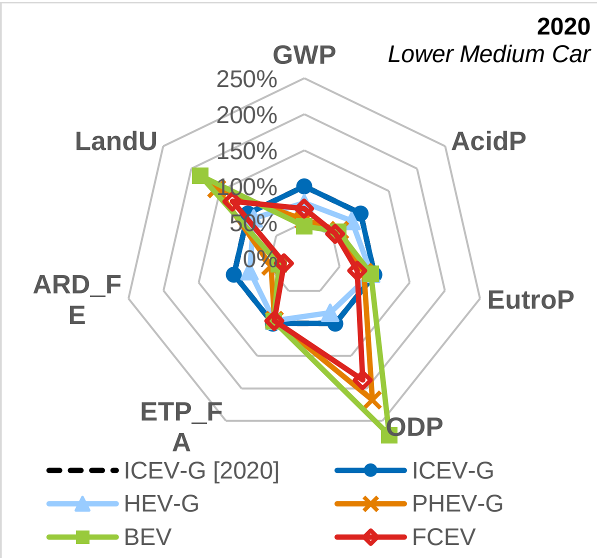
The following Figure 5.65 also provides a summary of relative impacts (versus a 2020 gasoline ICEV comparator) for different powertrain types for some of the less significant impact mid-points by powertrain type. The results for these other impacts mid-points appear to be more variable, and only some of these categories are significant for the road transport sector, compared to other sectors: notably ODP, eutrophication and land use (with the latter two primarily impacted by agriculture). The results in Figure 5.65 have been presented using the default fossil comparator fuel types, rather than the baseline or Tech1.5 scenario blends. This is because of unusual (negative) impact results for the land use impact category due to the co-product substitution and counterfactuals used in the applied methodology (discussed also in earlier section 5.3), which otherwise present a confusing relative comparison.

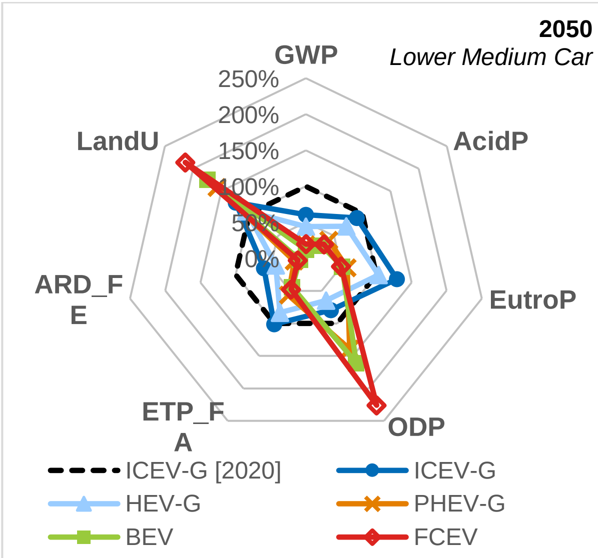
Impacts are significantly higher for both AcidP and EutroP for diesel ICEV (due to NOx emissions), and significantly lower for increasingly electrified powertrains. Impacts for the ODP are dominated by fuel production impacts, with overall impacts being highest for PHEV and BEV powertrains due to electricity production – mainly resulting from impacts from biomass and coal generation. However, ODP impacts are not significant overall for road transport compared to others (as illustrated in earlier Figure 3.2).

For freshwater ETP, xEVs have relatively higher impacts in 2020 due mainly to battery materials: copper in the anode, the nickel sulphate cathode precursor used in battery manufacturing, and the electronics in the battery periphery. However, these impacts reduce in later periods, and as discussed earlier, this mid-point indicator has a lower level of robustness and so has a relatively low final weighting factor recommended by JRC (see Table 3.5) (Ceruttin, Sala, & Pant, 2018).

The relatively higher land use impacts for PHEV, BEV and FCEVs result mainly from electricity consumption, with impacts being highest for biomass, wind and solar generation (with biomass >> wind > solar).

Figure 5.65: Summary of the relative impacts for Lower Medium Cars for other less significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Tech1.5 Scenario.





Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. Results are presented for default (fossil) comparator fuel types. GWP = Global Warming Potential, AcidP = Acidifying Potential, EutroP = Eutrophication Potential, ODP = Ozone Depletion Potential, ETP_FA = Freshwater Aquatic Eco-Toxicity Potential, ARD_FE = Abiotic Resource Depletion, fossil energy, LandU = Land Use

5.4.2 Other vehicle types

The following sections present a summary of the key results for rigid and articulated lorries and for urban buses, plus a higher-level summary of the differences for the other vehicle types. The discussion on the results for these vehicle types focusses on highlighting similarities and differences to the findings already presented for lower medium cars, and the reasons for this. Further information is also provided in Appendix A5 on the results for the other vehicle types (i.e. also for large SUV cars, N1 Class III vans, and for coaches).

5.4.2.1 Rigid lorries

The following Figure 5.66 provides a summary of the overall LCA results for small rigid lorries for the GWP impact category, showing also the breakdown of the results between different lifecycle stages.

The results of the analysis show similar trends as seen as for passenger cars, even accounting for the relatively conservative assumptions on lost load capacity/tonne-km for vehicles with heavier powertrains (i.e. assuming the average % loading by mass is similar for all powertrains). However, the difference between BEV and FCEV powertrains is larger than for cars, particularly in periods after 2020. This is due to the higher lifetime km activity of these vehicles, and the lower impacts due to operational energy use for BEVs. Vehicle manufacturing emissions are consequently a significantly smaller share of the overall impacts, compared to cars. FCEV-REEVs (FCEVs that can also be charged up to run off electricity from a larger on-board battery), show some additional benefits over regular FCEVs.

Results are also presented in Figure 5.66 for three alternative natural gas (or low carbon equivalent)-fuelled powertrains:

(i) *ICEV-CNG*: A conventional CNG spark-ignition (SI) engine vehicles (with ~17% higher energy consumption versus diesel ICEV)

(ii) *ICEV-CNGL*: A CNG lean-burn SI engine alternative (with ~4.5% energy penalty versus diesel ICEV, based on Ricardo testing of such engines currently still in development)

(iii) *ICEV-LNGD*: An LNG HPDI (high-pressure diesel injection) engine dual-fuel vehicle which uses ~5% diesel fuel and ~95% LNG (liquefied natural gas) on average during operation (estimated at only 3% energy efficiency penalty vs conventional diesel ICEV)

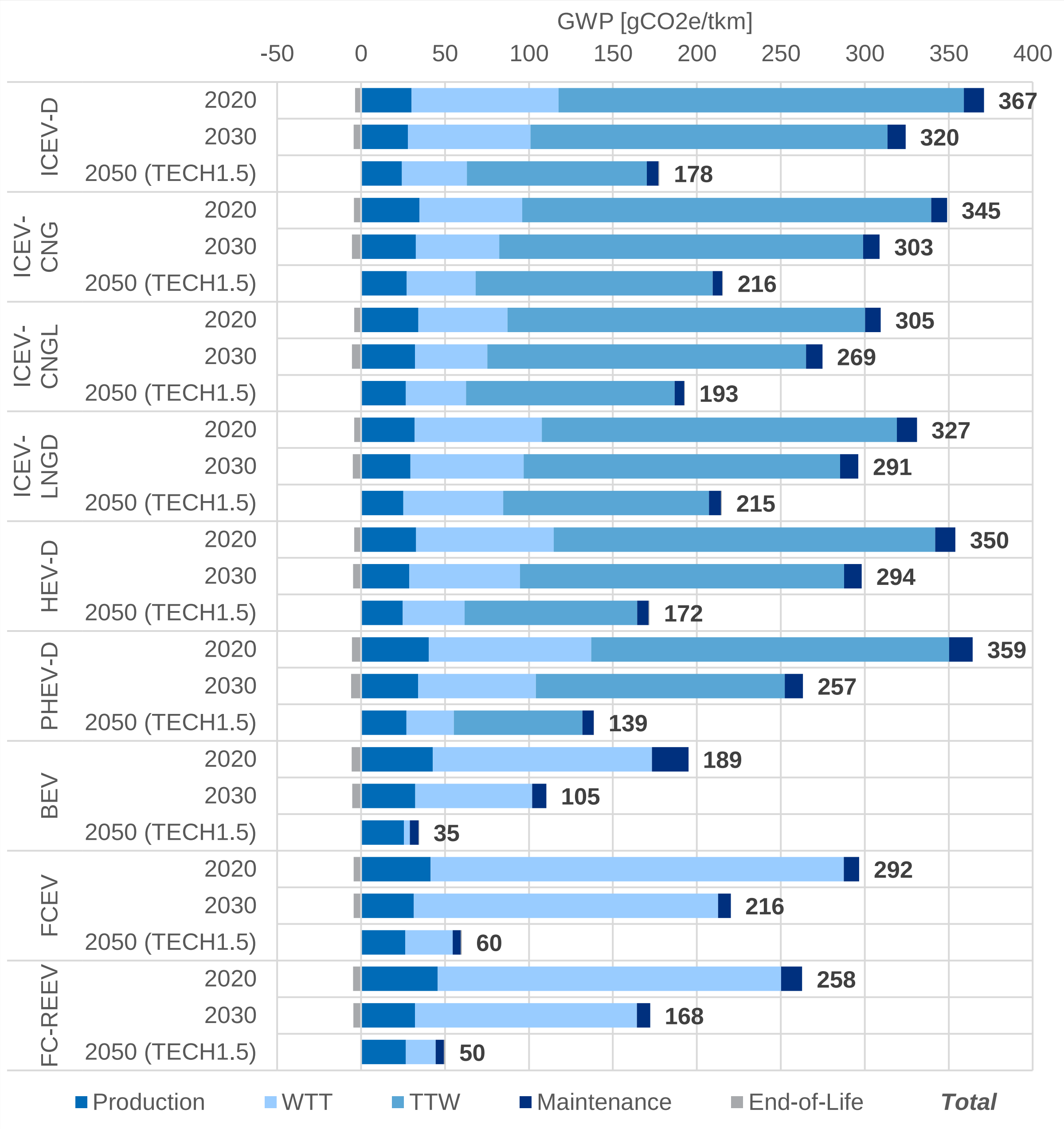
All three alternatives show benefits/lifecycle GHG reductions versus conventional diesel ICEVs due to the lower WTT and TTW emissions of gas (per MJ) compared to diesel fuel. Regulatory (Euro standard) limit values for tailpipe methane(-slip) emissions are in place for gas fuelled vehicles (TransportPolicy.net, 2019); our initial analysis showed that CH_4 emissions at 50-100% of the current limits (which are lower than historical real-world testing of dual-fuel vehicles) would still lead to significantly increased GHG emissions of dual-fuel gas-diesel compression-ignition (CI) engines vehicles versus the historically lower emissions from more conventional spark-ignition (SI) engined alternatives. However, recently published real-world performance analysis of gas vehicles has demonstrated methane slip for the newest technology vehicles to be relatively low in real-world conditions for all powertrain types (Cenex, 2019) meaning LNG CI vehicle powertrains perform better than SI LNG alternatives for GHG, CED. The -CNGL variants perform best in terms of GHG and CED, due to lower losses in fuel production (i.e. due to liquefaction for LNG). However, -LNGD vehicles also provide more compact gaseous fuel storage, enabling a longer gas-fuelled range compared to the other variants, which is more likely to be favoured in longer-distance (e.g. regional delivery) freight operations.

Under default conditions (assuming statistical average real-world mileage shares by road type for all rigid lorries), HEVs and PHEVs show relatively low or no lifecycle benefits (respectively) in 2020. These powertrains do show some benefits versus conventional diesel ICEVs in later periods after 2020. However, Figure 5.67 shows that more efficient operation over urban delivery conditions results in more significant benefits for these vehicle types as well as for gas-fuelled vehicles and BEVs. Conversely the alternative powertrains show fewer benefits (or even higher emissions for HEVs) when operating on the regional delivery cycle. These results underline the importance of matching different vehicle types to their anticipated real-world duty cycles, to ensure/maximise net benefits.

The results from the two figures also show that impacts from maintenance are relatively significantly higher for PHEV and BEV in 2020 (only) due to the need for a mid-life battery replacement as a result of higher lifetime km activity versus passenger cars (where no replacements are typically required). From 2030 onwards, no battery replacements are calculated to be required due to a combination of increased battery size and greater cycle life[27]. In part due to this element, PHEVs show essentially no lifecycle benefits versus diesel ICEVs in 2020 under the default assumptions, but show more significant benefits after 2020.

[27] Battery replacements are calculated in the model based on the size (capacity in kWh) of the battery, the battery cycle life, and the total lifetime activity (which determines the total energy throughput and therefore battery charge/discharge cycles required).

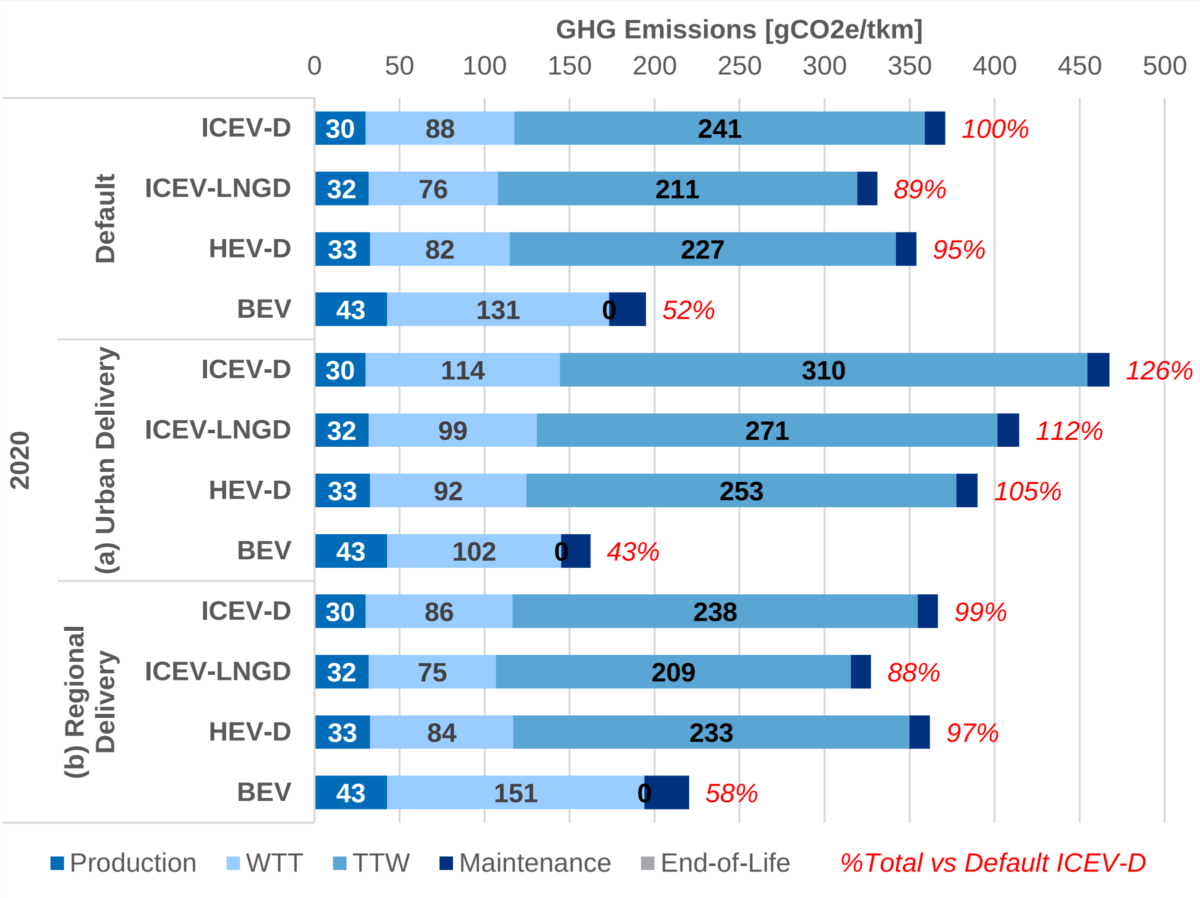
Figure 5.66: Summary of breakdown of overall lifecycle GWP impacts for Rigid Lorries (12t GVW, Box Body) for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types affects freight capacity, influencing the results.

2020	ICEV-D	ICEV-CNG	ICEV-CNGL	ICEV-LNGD	HEV-D	PHEV-D	BEV	FCEV	FC-REEV
Unladen mass, kg	6,146	6,435	6,378	6,319	6,304	6,889	7,067	6,423	6,913
% ICEV-D	*100%*	*105%*	*104%*	*103%*	*103%*	*112%*	*115%*	*104%*	*112%*
Lifetime tkm (thousands)	1,318	1,252	1,265	1,278	1,282	1,148	1,108	1,254	1,143
% ICEV-D	*100%*	*95%*	*96%*	*97%*	*97%*	*87%*	*84%*	*95%*	*87%*

Figure 5.67: Summary of the influence of driving cycle assumptions on overall 2020 lifecycle GWP impacts for Rigid Lorries (12t GVW, Box Body) for a selection of powertrain types



Notes: EU vehicle statistics have higher shares of regional and motorway km versus VECTO regulatory cycles

Default	Alternative
• ~550,000 km lifetime (EU Av.) • Battery cell manuf. current • Electricity EU av. lifetime • Av. EU 'Real-world' MJ/km • EoL: Recycling credits, low 2nd life battery share	a) Urban Delivery Cycle – road share and energy consumption b) Regional Delivery Cycle – road share and energy consumption

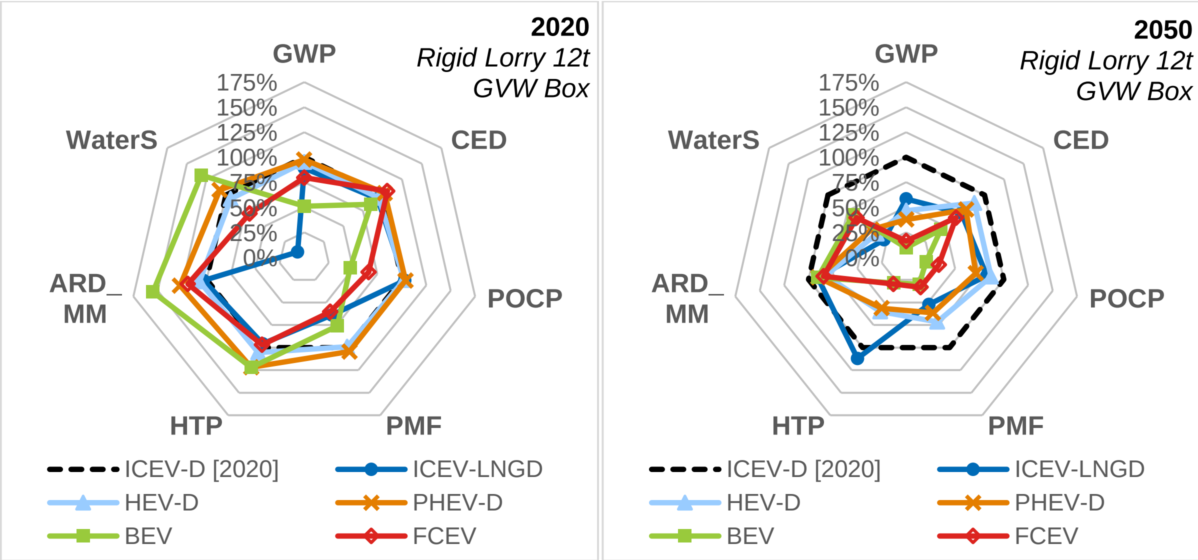
In terms of other lifecycle impacts, the following Figure 5.68 provides a summary of the relative performance of a number of different powertrain types for the most significant mid-point impacts. The results show that the 2020 life-cycle impacts for xEVs (especially BEV) are *higher* than conventional diesel and gas powertrain vehicles across a range of impact categories (mainly those associated with non-tailpipe emissions, i.e. HTP, ARD for minerals & metals, and water scarcity).

Similarly as for cars, the higher impacts for ARD_MM and HTP for xEVs are mainly due to the vehicle (battery) materials. In addition, lifetime impacts are compounded in 2020 due a battery replacement being required for 2020 BEV and PHEV powertrain vehicles, which is not necessary in future periods.

Also as for cars, the higher impacts for xEVs for the water scarcity impact mid-point is mainly due to due to operational electricity consumption (mostly due to coal generation in 2020, and due to solar/nuclear in 2050).

The impacts for xEVs all progressively reduce, versus other non-electric/electrified powertrains, in the years after 2020.

Figure 5.68: Summary of the relative impacts for Rigid Lorries (12t GVW, Box Body) for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Baseline Scenario.



Notes: LNGD = LNG HPDI engine, using ~5% diesel (estimated at only 3% energy efficiency penalty vs conventional diesel).

5.4.2.2 Articulated lorries

The following Figure 5.69 provides a summary of the overall LCA results for large articulated lorries for the GWP impact category, showing also the breakdown of the results between different lifecycle stages.

The results of the analysis show similar trends seen as for passenger cars and rigid lorries, even accounting for relatively conservative assumptions on lost load capacity/tonne-km for vehicles with heavier powertrains (i.e. assuming the average % loading by mass is similar for all powertrains). This lost load capacity is particularly high for BEVs in 2020, where almost a third of the freight capacity is taken up by batteries to achieve a 500km electric range, but significantly declines in later years (due to anticipated improvements in battery energy density).

As for cars and rigid lorries, BEV powertrains show significantly greater lifecycle benefits than FCEV powertrains in all scenarios and periods, due to their higher efficiency leading to lower operational energy impacts (also factoring in the hydrogen and electricity production chain efficiencies) and the very high lifetime km of articulated lorries. This differential also further increases in later years.

In terms of impacts, the results of the analysis show significant GWP benefits of -ERS vs non-ERS powertrains – i.e. those vehicles that can operate on electricity via an overhead catenary electric road system (ERS). For BEV-ERS powertrains, this is due to the lower battery size/mass versus a regular BEV. However, it should be noted that no information was available on the impact of additional drag that (-ERS) vehicles utilising a pantograph might have on operational energy consumption, which would likely counter-act such benefits.

Results are also presented in Figure 5.69 for two alternative natural gas (or low carbon equivalent)-fuelled powertrains. Due to the longer-ranges required for articulated lorries, CNG storage is not sufficient, and LNG is preferred:

(i) *ICEV-LNG*: A conventional LNG spark-ignition (SI) engine vehicles (with ~17% higher energy consumption versus diesel ICEV)

(ii) *ICEV-LNGD*: An LNG HPDI (high-pressure diesel injection) engine dual-fuel vehicle which uses ~5% diesel fuel and ~95% LNG (liquefied natural gas) on average during operation (estimated at only 3% energy efficiency penalty vs conventional diesel ICEV)

Both gas powertrain variants show net lifecycle benefits versus conventional diesel ICEVs due to the lower WTT and TTW impacts of gas fuel versus diesel. However, similarly to the case for rigid lorries, the higher efficiency of the LNG HPDI powertrain (versus conventional LNG SI engine), means the overall lifecycle GWP impacts are lower for such powertrains.

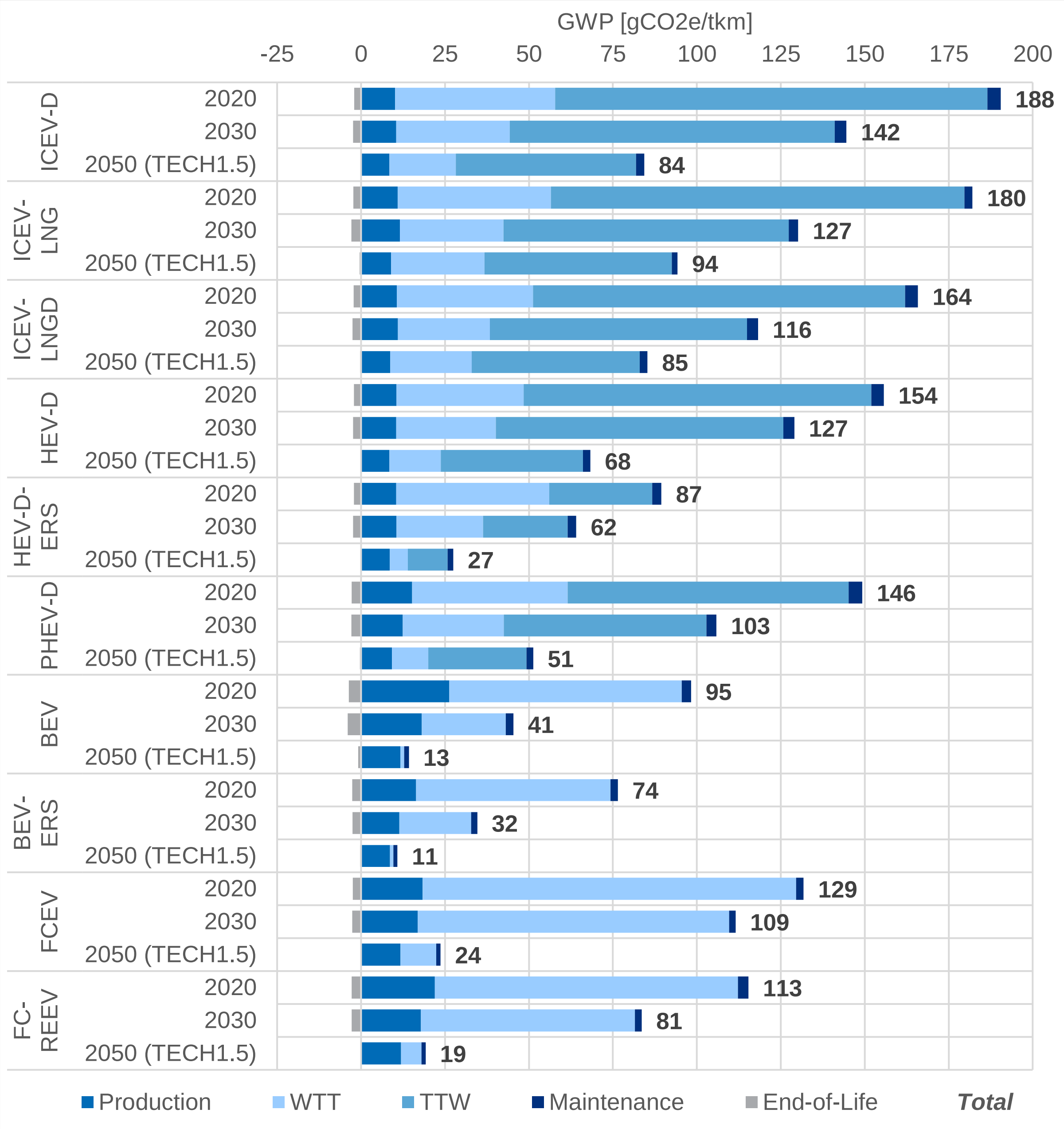
In terms of impacts from vehicle maintenance, the analysis shows higher impacts for PHEVs and BEVs for 2020 vintage vehicles only, due to the calculated requirement for a battery replacement. As for rigid lorries, a combination of larger (capacity) and greater cycle life batteries means that from 2030 onwards, no battery replacements are calculated to be required under the default assumptions[28].

The EU vehicle activity statistics that are also used in modelling analysis for the EC (and upon which the real-world energy consumption/impacts have been based) show relatively significantly higher shares of urban and regional km versus those on the VECTO regulatory cycles that have been developed for whole vehicle fuel consumption and CO_2 emission certification for lorries. Figure 5.70 shows that the lifecycle analysis results are significantly lower when assuming operation on these regulatory cycles, mainly due to lower shares of less efficient urban road operation. The reasons for this differential are not clear, however it may be due to weaknesses in the collection of statistical data on heavy lorry activity, since information collected directly from operators typically suggests relatively lower shares of urban activity are typical in most applications for such large vehicles.

The more efficient average operation of conventional diesel ICEVs over the VECTO cycles results in lower relative benefits for all of the alternative fuelled vehicle types – particularly for the long-haul duty cycle. Nevertheless, these powertrains still all show significant net benefits over conventional diesel ICEV equivalents. However, these results do also underline the importance of matching different vehicle types to their anticipated real-world duty cycles, to ensure/maximise net benefits.

[28] Battery replacements are calculated in the model based on the size (capacity in kWh) of the battery, the battery cycle life, and the total lifetime activity (which determines the total energy throughput and therefore battery charge/discharge cycles required).

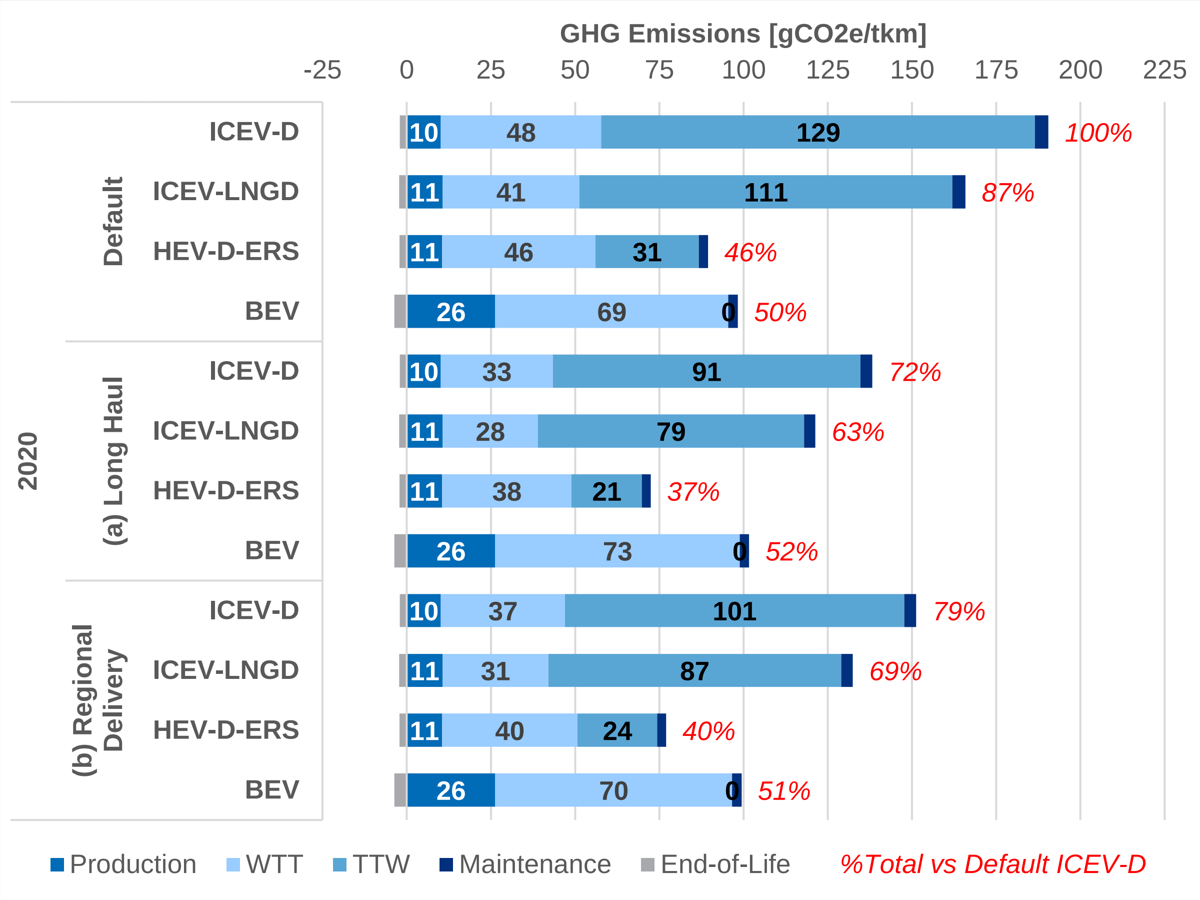
Figure 5.69: Summary of breakdown of overall lifecycle GWP impacts for Articulated Lorries (40t GVW, Box Body) for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types affects freight capacity, influencing the results.

2020	ICEV-D	ICEV-LNG	ICEV-LNGD	HEV-D	HEV-D-ERS	PHEV-D	BEV	BEV-ERS	FCEV	FC-REEV
Unladen mass, kg	14,469	14,596	14,842	14,576	14,644	16,766	20,943	16,991	15,944	17,764
% ICEV-D	*100%*	*101%*	*103%*	*101%*	*101%*	*116%*	*145%*	*117%*	*110%*	*123%*
Lifetime tkm (thousands)	8,146	8,105	8,026	8,112	8,090	7,411	6,074	7,339	7,674	7,091
% ICEV-D	*100%*	*100%*	*99%*	*100%*	*99%*	*91%*	*75%*	*90%*	*94%*	*87%*

Figure 5.70: Summary of the influence of driving cycle assumptions on overall 2020 lifecycle GWP impacts for Articulated Lorries (40t GVW, Box Body) for a selection of powertrain types



Notes: EU vehicle statistics have higher shares of urban and regional km versus VECTO regulatory cycles

Default	Alternative
• ~800,000 km lifetime (EU Av.) • Battery cell manuf. current • Electricity EU av. lifetime • Av. EU 'Real-world' MJ/km • EoL: Recycling credits, low 2nd life battery share	a) Long Haul Cycle – road share and energy consumption b) Regional Delivery Cycle – road share and energy consumption

In terms of other lifecycle impacts, the following Figure 5.71 provides a summary of the relative performance of a number of different powertrain types for the most significant mid-point impacts for articulated lorries. Similarly to rigid lorries (and cars), the results show that the 2020 life-cycle impacts for xEVs (especially BEV) are *higher* than conventional diesel and gas powertrain vehicles across a range of impact categories (mainly those associated with non-tailpipe emissions, i.e. HTP, ARD for minerals & metals, and water scarcity). However, the differentials to conventional diesel ICEV are higher than for rigid lorries, due to the particularly large batteries required for the longer-range operation typical of articulated lorries (i.e. assumed to be 500km in 2030 for BEVs, rising to 1500km by 2050).

Similarly as for cars and rigid lorries, the higher impacts for ARD_MM and HTP for xEVs are mainly due to the vehicle (battery) materials, and for gas/hydrogen storage for LNG/LNGD and FCEV powertrains, respectively. In addition, lifetime impacts are compounded in 2020 due a battery replacement being required for 2020 BEV and PHEV powertrain vehicles, which is not necessary in future periods.

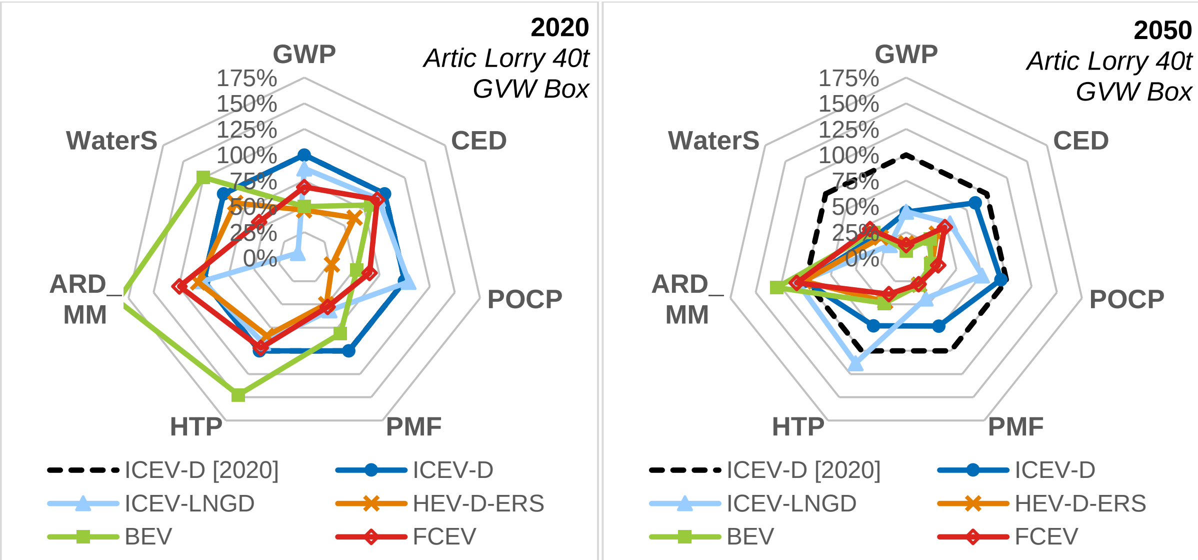
Gas-fuelled powertrains (e.g. ICEV-LNG/LNGD) show significant non-GHG benefits across a number of impact categories vs diesel ICEV. In addition, the HEV-D-ERS powertrain shows significant reduction in most of the other impact categories, with significantly reduced negative impacts on ARD_MM and

HTP in 2020 in comparison to other electrified powertrain types, mainly due to smaller batteries. The relative benefits of this powertrain progressively diminishes in the periods after 2020.

Also as for cars and rigid lorries, the higher impacts for xEVs for the water scarcity impact mid-point is mainly due to due to operational electricity consumption (mostly due to coal generation in 2020, and due to solar/nuclear in 2050). These effects are further exacerbated by the higher lifetime mileage of articulated lorries.

The impacts for xEVs all progressively reduce, versus other non-electric/electrified powertrains, in the years after 2020.

Figure 5.71: Summary of the relative impacts for Articulated Lorries (40t GVW, Box Body) for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Baseline Scenario.



Notes: LNGD = LNG HPDI engine, using ~5% diesel (estimated at only 3% energy efficiency penalty vs conventional diesel); HEV-D-ERS = Hybrid with pantograph enabling electric operation on roads equipped with an overhead catenary electric road system (ERS)

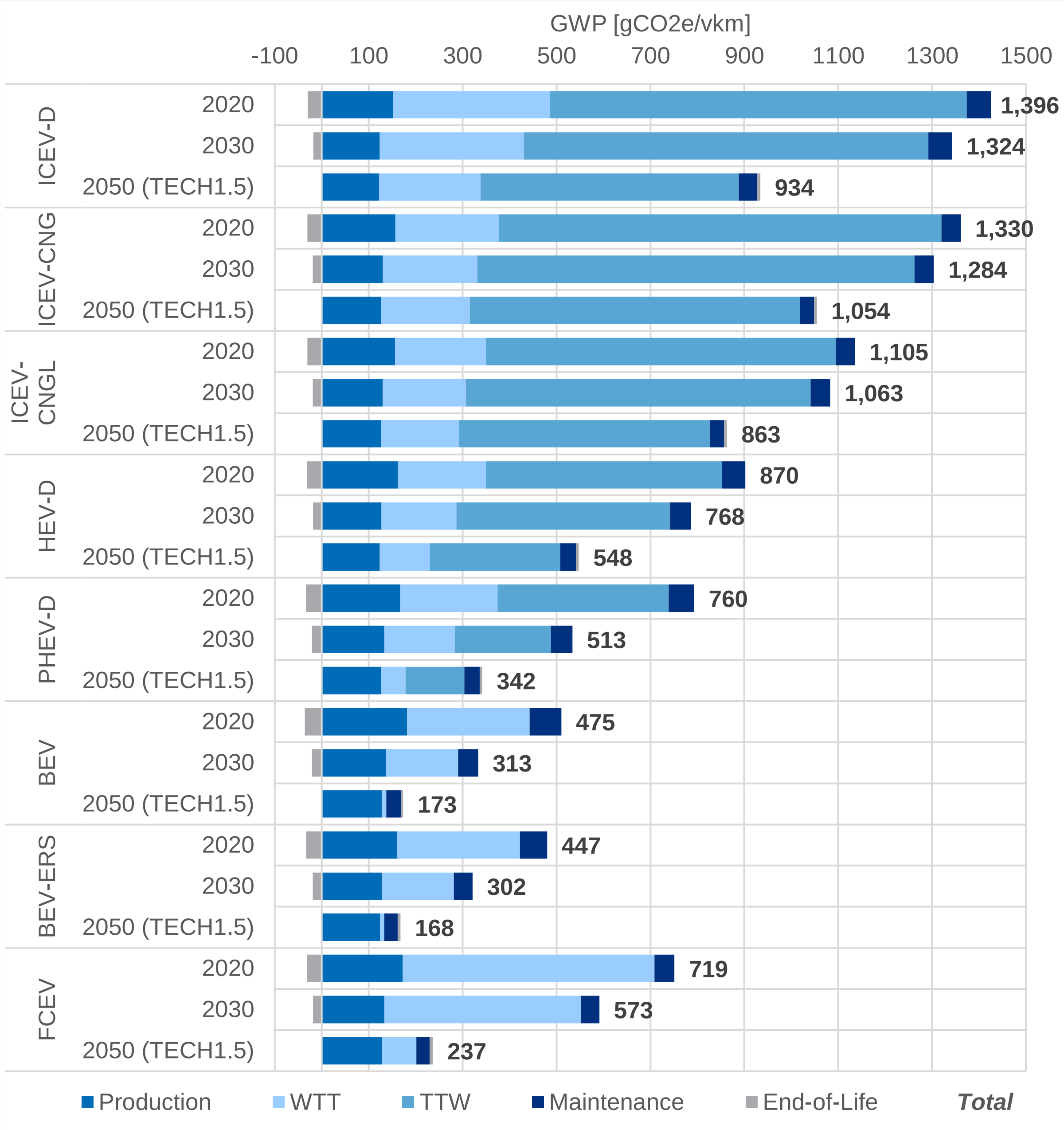
5.4.2.3 Urban buses

The following Figure 5.72 provides a summary of the overall LCA results for urban buses for the GWP impact category, showing also the breakdown of the results between different lifecycle stages.

The results of the analysis show more extreme trends as seen as for passenger cars and lorries, with the urban operation setting further enhancing the benefits for gas-fuelled vehicles, hybrids and xEVs compared to conventional powertrain types. The BEV-ERS powertrain type included here assumes a smaller battery and more regular ultra-rapid charging/topping up along the bus route using a pantograph-based charging system located on the top of the bus (and not the continuous dynamic charging/operation assumed for articulated lorries using overhead catenaries on major interurban roads). The results show significant benefits for gas-fuelled powertrains versus conventional diesel ICEV (due to lower WTT and TTW emissions from CNG). However the urban setting leads to significantly greater savings for hybrids and for other xEVs.

As for the other heavy-duty vehicle types, there are higher maintenance impacts in 2020 for hybrids, PHEVs and BEVs due to a mid-life battery replacement being required. Again, no replacements are calculated to be required for later years after 2020.

Figure 5.72: Summary of breakdown of overall lifecycle GWP impacts for urban buses (12m single deck) for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types also influences the overall results.

2020	ICEV-D	ICEV-CNG	ICEV-CNGL	HEV-D	PHEV-D	BEV	BEV-ERS	FCEV
Unladen mass, kg	11,944	12,165	12,108	12,275	12,754	13,207	11,735	12,041
% ICEV-D	*100%*	*102%*	*101%*	*103%*	*107%*	*111%*	*98%*	*101%*
Lifetime vkm (thousands)	675	675	675	675	675	675	675	675
% ICEV-D	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*

In terms of other lifecycle impacts, the following Figure 5.73 provides a summary of the relative performance of a number of different powertrain types for the most significant mid-point impacts. The results show that the 2020 life-cycle impacts for xEVs are only marginally better than conventional diesel and gas powertrain vehicles across a range of impact categories, unlike for other vehicle types. This is likely due to relatively smaller battery requirements due to a combination of lower range requirements compared to other HDVs and more efficient urban operation.

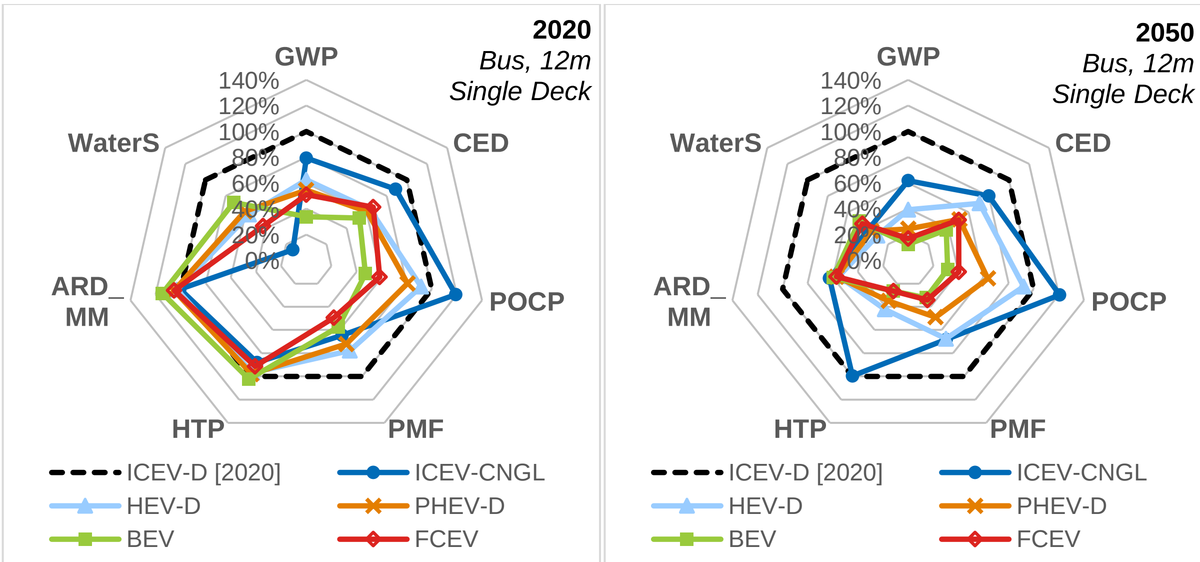
Similarly as for other vehicle types, the higher impacts for ARD_MM and HTP for xEVs are mainly due to the vehicle (battery) materials, with higher impacts also due to battery replacement requirements in 2020 (only). Whilst these impacts are greater for BEVs versus FCEVs in 2020, by 2050 the impacts are higher for FCEVs across all impact categories for urban buses. The benefits of FCEV are greater versus BEVs in 2020 in part due to lower impacts from hydrogen production from gas (via SMR), but similar or lower by 2050 where hydrogen is assumed to be produced from a mix of SMR (or SMR+CCS in the Tech1.5 scenario) and electrolysis.

xEV powertrains show significant benefits due to reduction in air quality pollutants contributing to POCP, PMF. Gas powertrains (e.g. ICEV-CNGL) also show significant non-GHG benefits across a number of categories vs diesel, except for POCP (due to upstream/WTT emissions).

Unlike other vehicle types, the impacts for xEVs for the water scarcity impact mid-point are actually lower than for all alternative powertrain types (due to higher operational efficiency in the urban setting).

The impacts for xEVs all progressively reduce, versus other non-electric/electrified powertrains, in the years after 2020.

Figure 5.73: Summary of the relative impacts for urban buses (12m single deck) for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Baseline Scenario.



Notes: CNGL = CNG Lean-burn engine (estimated at only 3% energy efficiency penalty vs conventional diesel)

5.5 Sensitivities on key parameters for the overall vehicle LCA

This section provides an overview of the main sensitivities modelled and their effects on the overall results. The outcomes from this analysis are generally presented in this section for GWP impacts of a lower medium car in a specific year, under the baseline scenario, except where relevant to present results for other cases. Where possible, a brief commentary is provided on the conclusions from the sensitivity analysis for other vehicle types, impact categories and periods. Full results are provided in the accompanying results database files and 'Vehicle LCA Results Viewer' (see Section 4.6).

5.5.1 Summary of sensitivities

In total, 14 different sensitivities were modelled to understand the importance of key parameters or assumptions for determining GHG emissions and other LCA impacts over the life cycle of different vehicles. The inclusion/prioritisation of these sensitivities has been informed both by the literature review and the consultation with expert LCA stakehodlers. As Table 5.2 illustrates, these sensitivities cover different aspects from the vehicle life cycle, ranging from alternative assumptions on vehicle operation (e.g. lifetime kilometre activity) to variations in vehicle specification parameters (e.g. electric range) as well as alternative scenarios for vehicle production and end-of-life processes (e.g. second-life applications of batteries). Their effects on the LCA results are presented in the subsequent sections.

Table 5.2: Summary of vehicle LCA modelling sensitivities

Sensitivity	Description	Variations	Area
Regional variations	Examples of variation in impacts for different EU regions (i.e. due to different road mileage shares, electricity mix)	EU28, DE, LU, PL, SE (though any individual EU28 country is possible)	Vehicle Operation
Lifetime km	Low or high lifetime vehicle mileage assumptions	Default / Low / High	Vehicle Operation
PHEV fuel share	Impact of different share of operation on electricity (e.g. due to use profile / charging behaviour)	Default / Low / High	Vehicle Operation
Loading	Impact for alternative assumptions on vehicle loading (with impacts on energy consumption, and also on tonne-km due to lower payload capacity for heavier powertrains)	Average / Full (100% loading)	Vehicle Operation
Future ICE AQP	Alternative scenario with significant future tailpipe air quality pollutants (AQP)reduction (e.g. due to possible future Euro 7/VII standards and beyond)	Default / Improved	Vehicle Operation
Ambient temperature	Sensitivity exploring the relative impact for different powertrain types of operating 100% at very low or very high ambient temperatures. (Data only available for light-duty vehicles.)	Default / -10 °C / -10 °C (HP) / +35 °C *	Vehicle Operation
Fuel chain methodology	Sensitivity illustrating the impact of varying the different methodological basis for the fuel chain calculations feeding into the fuel blends.	Energy allocation (Default) / Energy allocation +Counterfactual (CF) / Substitution + CF	Vehicle Operation
Glider	Alternative trajectories for glider material composition (set linked to or independently of overall scenario setting - to allow for examination of material-specific impacts)	Default, TECH1.5 Glider composition	Vehicle Specification
Electric range	Alternative assumptions for electric range for xEVs	Default / Low / High	Vehicle Specification
Battery energy density	Alternative assumptions on battery technology improvement / future chemistries, impacting particularly on energy density	Default / Low / High	Vehicle Specification
Battery EUSVC **	Sensitivity on EU sustainable value chain for battery manufacturing and end-of-life treatment	Default / EUSVC for battery production, battery EoL (can be set independently also)	Vehicle Production and End-of-Life
Vehicle EUSVC	Sensitivity on EU sustainable value chain for vehicle manufacturing and end-of-life treatment (non-battery)	Default / EUSVC for vehicle production, vehicle EoL (can also be set independently also)	Vehicle Production and End-of-Life

Sensitivity	Description	Variations	Area
Battery second life	Sensitivity on high share of xEV battery second life applications	Low shares (Default) / High	Vehicle Production and End-of-Life
Battery input data	Sensitivity on the source of input data for battery manufacturing – comparison of PEFCR and GREET manufacturing energy assumptions on the results	Default / GREET NMC EU / GREET NMC CN / PEFCR NMC EU / PEFCR NMC CN	Vehicle Production and End-of-Life

Notes: * Default = regulatory test cycle average temperature, HP = Heat Pump included for xEVs (reduces low temperature heating energy demand); **EU Sustainable Value Chain = use of renewable energy for manufacturing and end-of-life recycling, improved recycling recovery rates versus baseline/default, and higher share of EU manufacturing of batteries.

5.5.2 Sensitivity on variations within the EU

A sensitivity analysis on regional activity, electricity generation mix, and ambient temperature was performed to understand the extent of variations in the impacts of driving vehicles in different EU Member States. The following differences between countries are considered:

- Road mileage shares (i.e. percentage of driving in different road types) will vary with the road network and geography of the country. These determine average speeds and other driving conditions that affect the vehicle's energy consumption and tailpipe emissions.
- Grid average electricity impacts will differ depending on the country's electricity mix. This affects the level of impacts during the use phase of xEVs.
- Climate conditions also vary, with some countries experiencing more extreme ambient temperatures. These will also influence energy consumption of all powertrain types due to the use of auxiliary systems (i.e. heating and cooling). For xEVs in particular, electric range is also impacted.

Figure 5.76 shows the GWP impact results for Germany (DE), Luxembourg (LU), Poland (PL) and Sweden (SE), in addition to the EU28 average. Values in red on the graph represent the GWP impact as a percentage of the EU28 ICEV-G (i.e. gasoline ICEV) impact. Although the model allows for more countries to be specified, we have selected these four as they represent a wide set of circumstances in terms of road mileage shares, electricity generation mix and ambient temperature. Table 5.3 shows the variation in these key assumptions for each country plus the EU28 average.

As Figure 5.76 demonstrates, GWP impacts from a car in the selected EU Member States are similar to the EU28 average for the ICEV-G in 2020 (i.e. represent 100% - 105% of the impacts for EU28). This suggests that variations in road mileage shares and climate/ambient temperature lead to relatively small differences for ICE cars, with variations mainly stemming from the effects of these parameters on energy consumption and tailpipe CH_4 and N_2O emissions.

The effects of regional variations in electricity mix can be mainly observed in the GWP impacts from the BEV, where significant variation in the results is apparent in 2020 between the selected countries. In general, overall impacts tend to be lower for countries where the carbon footprint of electricity is much smaller (e.g. SE). This has important implications for the relative performance of the BEV compared to an ICEV-G in 2020: this sensitivity shows that the benefits of the BEV (in terms of lower GWP impacts) become less significant in countries where electricity is more carbon intensive (e.g. PL). This is in line with the findings from the literature that already demonstrated the importance of assumptions on electricity mix for the LCA results.

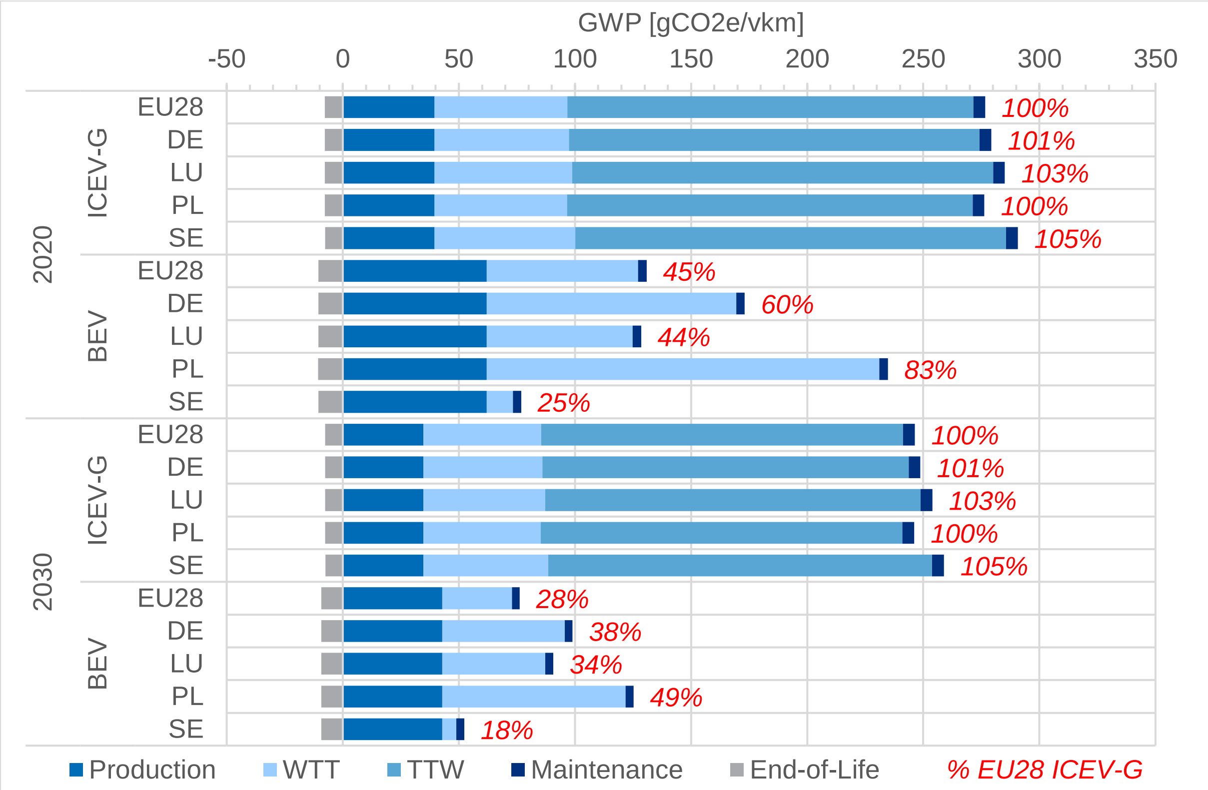
In Figure 5.75, an additional illustration is provided of the performance of BEVs in different EU countries, ranked by total impact, in comparison to the EU28 average for gasoline and diesel ICEVs and for BEVs. This shows that the net lifecycle impacts of new BEVs are anticipated to be lower than EU average new gasoline and diesel cars in all EU countries except for Estonia (EE) in 2020, under average driving conditions, and for all countries by 2030.

Table 5.3: Key assumptions on regional activity, electricity generation mix and ambient temperature for selected countries and regions, Lower Medium Car, Baseline Scenario

Region / Country	Regional activity assumptions (1)			Electricity generation impact, av. gCO_2e/MJ (2)		Annual av. ambient temperature, ºC (3)
	Urban	Rural	Motorway	2020	2030	
EU28	28%	57%	15%	92	54	10 ºC
Germany (DE)	27%	53%	20%	117	81	8.5 ºC
Luxembourg (LU)	63%	30%	7%	95	65	8.7 ºC
Poland (PL)	21%	74%	5%	250	149	7.9 ºC
Sweden (SE)	60%	32%	8%	16	12	2.1 ºC

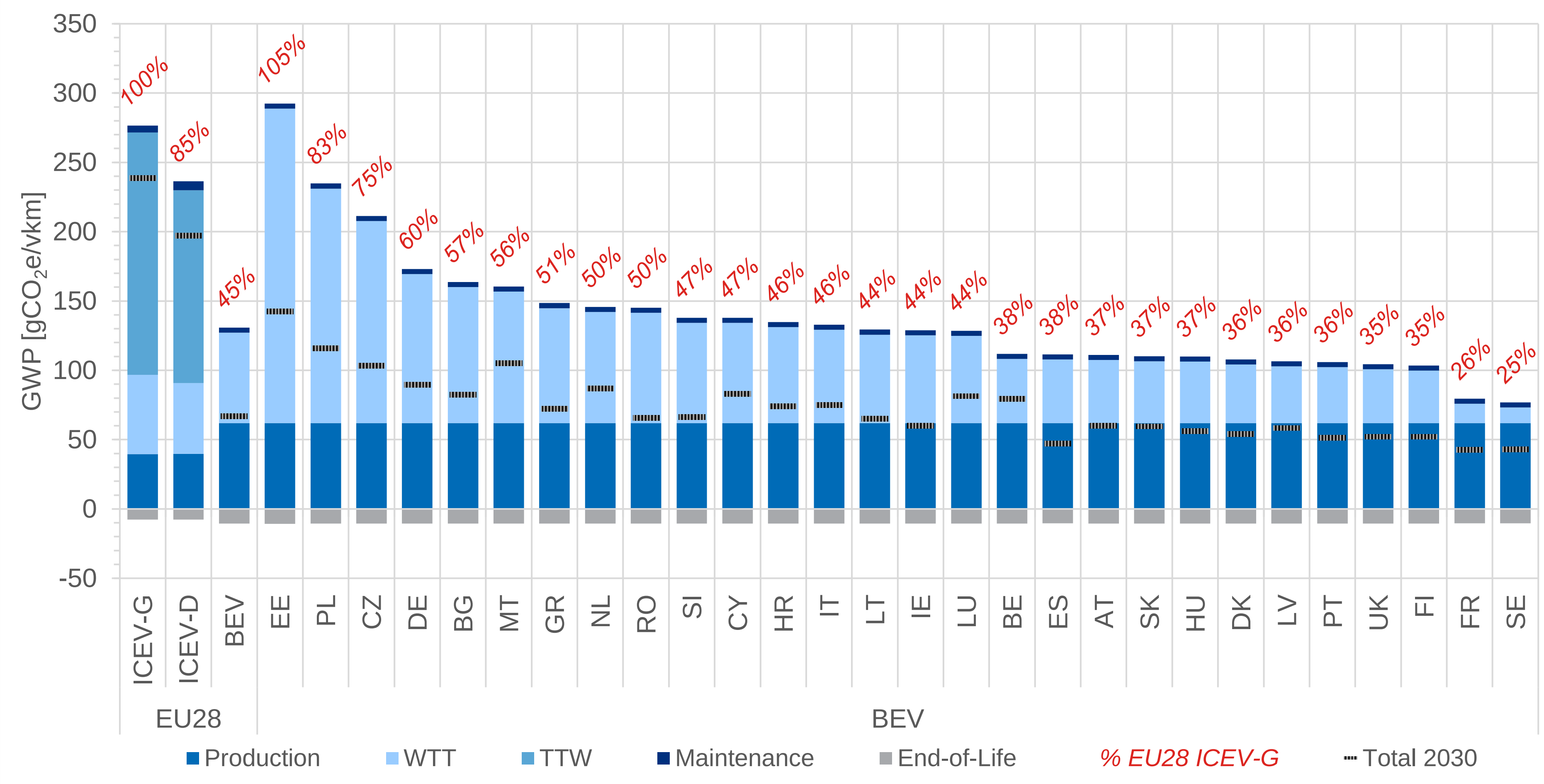
Notes: (1) Based on PRIMES-TREMOVE modelling data for EC scenario analysis; (2) Activity-weighted average over the lifetime of the vehicle; (3) Based on gridded climatologies from the Climatic Research Unit, extracted from Wikipedia

Figure 5.74: Effects of regional variation in road mileage shares, electricity mix and ambient temperature, Lower Medium Car, Baseline Scenario, 2020 and 2030



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEVs.

Figure 5.75: Comparison of Lower Medium Car lifecycle GWP impacts for conventional gasoline/diesel ICEVs and BEVs for different EU countries, Baseline scenario. Breakdown shown for new 2020 vehicles, and the total only for new 2030 vehicles.



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range (and with 64 kWh and 460 km WLTP electric range for 2030); an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEVs.

Over time, given the widespread trend towards decarbonisation of electricity in the EU, the effects of regional variation in electricity mix become smaller. As a result, the overall GWP impacts from the BEV are also lower in future periods (shown for 2030 in the figure) and the gap in the performance of the BEV versus the ICEV-G increases for all EU Member States. Similar effects are observed for other vehicle types.

It can therefore be concluded that using the EU28 average electricity mix to assess the impacts of vehicles is likely to hide significant differences in regional electricity mixes that affect the relative performance of powertrains and therefore their relative benefits in different EU Member States. These effects diminish over time as countries converge towards the use of lower carbon intensive sources of energy.

5.5.3 Sensitivity on lifetime kilometre activity

As concluded from the literature review (see Section 2.2.3.4), assumptions on the lifetime kilometre activity can significantly affect the LCA results. The alternative assumptions shown in Table 5.4 have therefore been examined.

Table 5.4: Assumptions on lifetime kilometre activity

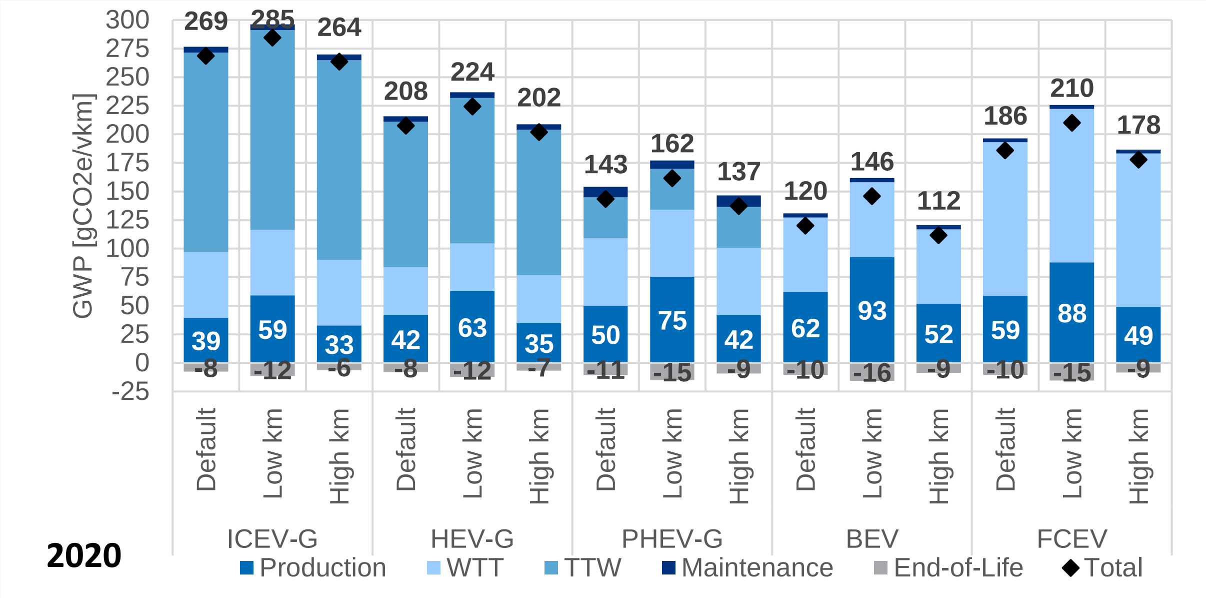
Vehicle type	Segment	Default	Low	High
Passenger car	Lower medium	225,000	150,000	270,000
Passenger car	Large SUV	270,000	180,000	300,000
LCV	N1 Class III	240,000	200,000	300,000
Rigid Lorry	12t GVW Box	570,000	420,000	720,000
Artic Lorry	40t GVW Box	800,000	600,000	1,000,000
Bus	12m SD	675,000	510,000	825,000
Coach	24t GVW SD	870,000	660,000	1,080,000

Figure 5.76 illustrates the results from this sensitivity for a car in 2020. In this case, this study's default assumption was compared to a lower value that is commonly used in the literature (150,000 km) and a slightly higher value representing an increase in lifetime kilometre activity of 20% (270,000 km). The default assumption is based on recent examination of detailed real-world data on lifetime km by LDVs in the EU (see Section 4.7.2), however the lower figure of 150,000 has often been used in previous LCA literature (particularly in OEM LCA studies) and has its roots in the durability/emissions warranty requirements for new vehicles from type-approval certification in the EU. The effects of this sensitivity can be observed in terms of a change in impacts per vkm from manufacturing and end-of-life stages. The impact of these stages in absolute terms is fixed and therefore their impacts when expressed in per vkm terms can significantly increase/decrease with the decrease/increase (respectively) of lifetime kilometre activity.

It follows that powertrain types for which the relative impacts from the manufacturing and end-of-life stages are more significant (i.e., xEVs and in particular BEVs) are also more affected by these assumptions. As a result, if a lower lifetime kilometre activity is assumed, the overall impacts from the BEV increase and its relative benefits (in terms of lower GWP impacts compared to the other powertrains) decrease (i.e. effect is more pronounced for BEVs and therefore the gap between this powertrain and the others decreases). For a higher lifetime kilometre activity, the inverse effects are observed. Despite the effects of lifetime kilometre activity on the relative performance of xEVs, these powertrains are still expected to outperform conventional vehicles for all the assumptions examined.

Although not illustrated here, the effect of this sensitivity on BEVs diminishes in future periods as impacts from the manufacturing stage are expected to reduce over time. As a result, the effect of varying assumptions on lifetime kilometre activity on the comparison of BEVs vs other powertrains also narrows in the future. In addition, the size of the effect in future periods for all powertrains also becomes lower due to the use of lower carbon energy.

Figure 5.76: Sensitivity on lifetime kilometre activity, Lower Medium Car, Baseline Scenario, 2020



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: 2020 BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

A similar conclusion can be drawn for vehicles characterised by a higher number of kilometres driven over their lifetime (i.e. HDVs). The effects are less significant for these vehicles as the relative contribution of the manufacturing and EoL stages to overall GWP impacts is also smaller, even for xEVs. For this reason, the relative difference between the BEV and other powertrains is also narrower.

Overall, this sensitivity shows that, in line with the conclusions from previous studies, assumptions on lifetime kilometre activity affect the size of LCA impacts per vkm. These effects are more significant for lower-kilometre vehicles (i.e. LDVs) and powertrains for which an important share of impacts originates from the production and EoL stages (i.e., xEV and BEVs in particular). Nevertheless, xEVs are still expected to outperform conventional powertrains, although their relative benefits become smaller at lower levels of lifetime kilometre activity. Over time, the importance of this assumption for the results is expected to become lower as the impacts from the production and EoL stages also become smaller. In addition, this also shows that vehicles (particularly BEVs) should ideally be designed for and used in applications where they are able to exploit all their 'available' lifetime mileage for maximum benefit.

5.5.4 Sensitivity on PHEV charging behaviour / share of electric mileage

This sensitivity explores an optimistic and pessimistic case for the electric driving share of a PHEV, compared to the default share assumed in this study. This is to account for differences in use profiles and charging behaviour of PHEVs which affect the share of electric driving of these vehicles.

The share of electric driving in a LDV PHEV has been calculated based on the WLTP LDV utility function (UF) represented in Figure 5.77 below. The default WLTP electric range (50 km in 2020, rising to 60km from 2030) has been adjusted to account for a lower real-word efficiency (44 km in 2020, rising to 53km in 2030) – see earlier Figure 4.4). Given that the utility function already assumes a high share of electric driving in the default scenario (72%), the pessimistic case represented by the low variant in the figure represents a higher change in the electric share of driving compared to the default scenario than the optimistic case (high variant in the figure). For this sensitivity, the share of electric driving is set to 45% and 82% in the low and high variants, respectively.

Figure 5.77: WLTP LDV utility function

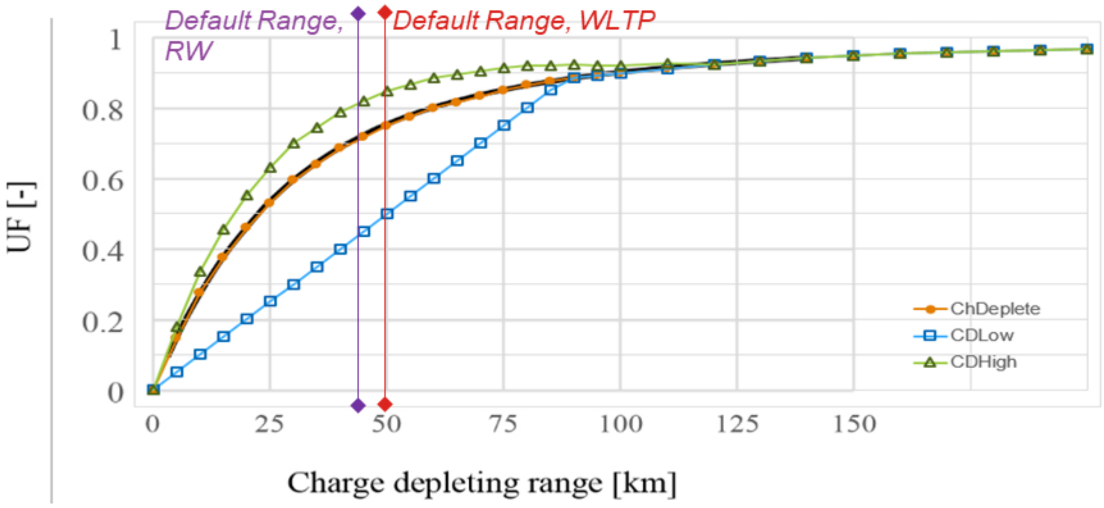
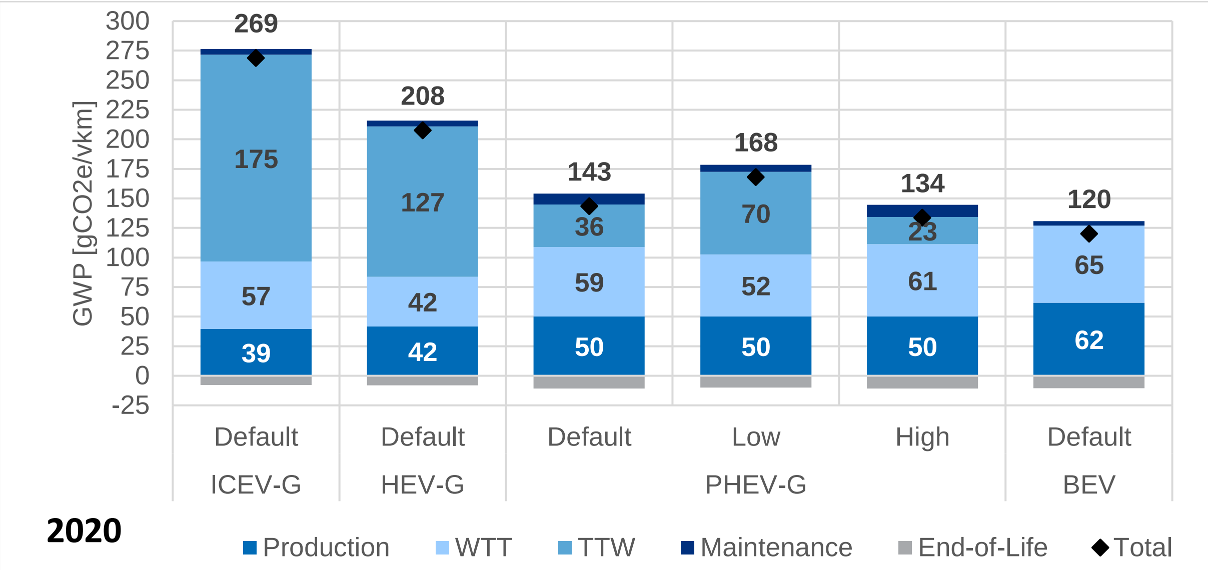


Figure 5.78 therefore shows that, for a car in 2020, the effects of this sensitivity on the PHEV-G are more significant for the pessimistic case (low variant in the figure). As expected, a lower share of electric driving is associated with higher overall impacts. The cases of HEV and BEV are also included as their impacts are similar to the impacts expected from assuming 0% or 100% electric driving, respectively, for the PHEV-G.

Over time, this sensitivity also becomes more relevant: differences between the default case and the variants become more pronounced. This is due to the fact that the benefits from electric driving increase with the decarbonisation of electricity.

It can therefore be concluded that differences in charging behaviour and use of PHEVs can significantly affect their net benefits.

Figure 5.78: Sensitivity on PHEV share of electric mileage, Lower Medium Car, Baseline Scenario, 2020



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.5 Sensitivity on vehicle loading

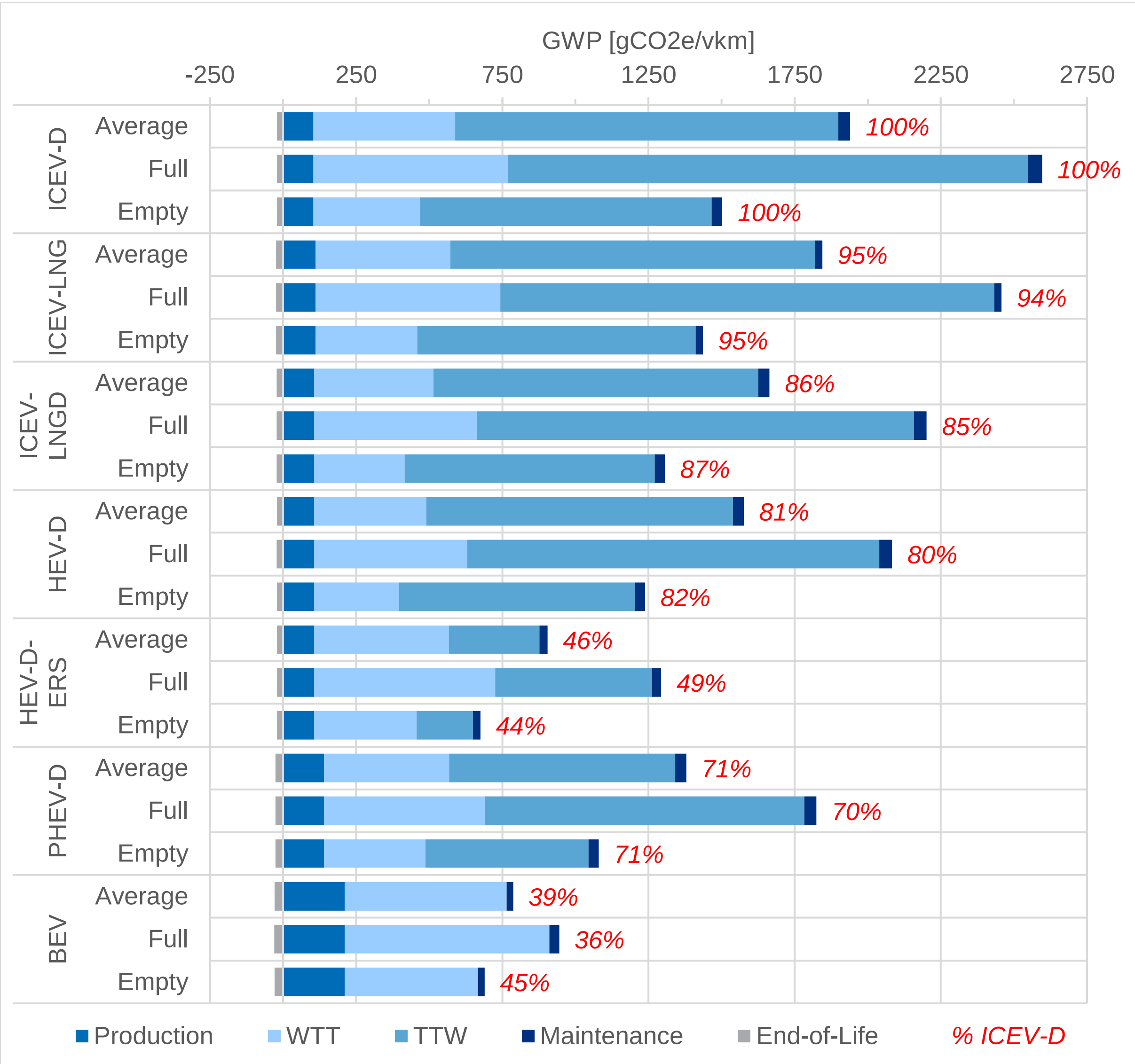
This sensitivity considers variations in the loading factor of HDVs and investigates the effects of differences in mass between conventional and alternative powertrains for higher loads. Variations in the average load factor have two type effects evidenced when impacts are expressed in terms of:

- Vehicle-km (vkm): for higher loads, higher energy consumption impacts per vkm are expected.
- Tonne-km (tkm): this varies with powertrain; for heavier powertrains which have lower payload capacity, impacts are uncertain depending on whether they are mass or volume limited.

Figure 5.79 shows the results of this sensitivity in terms of GWP impacts per vkm for an articulated lorry in 2020. It compares operation with the average load factor assumed for this study (of 40%) to operation with a full load (i.e., 100%) and with an empty load (0%). It finds that, although a high load factor increases the WTW energy impacts per vkm for all powertrains, it also magnifies the relative benefits of xEV per vkm (compared to the conventional powertrain) since the WTW impacts account for a much smaller share in this powertrain. For impacts expressed in per tkm terms (Figure 5.80), this effect is balanced out for BEVs due to reduced load capacity for 2020.

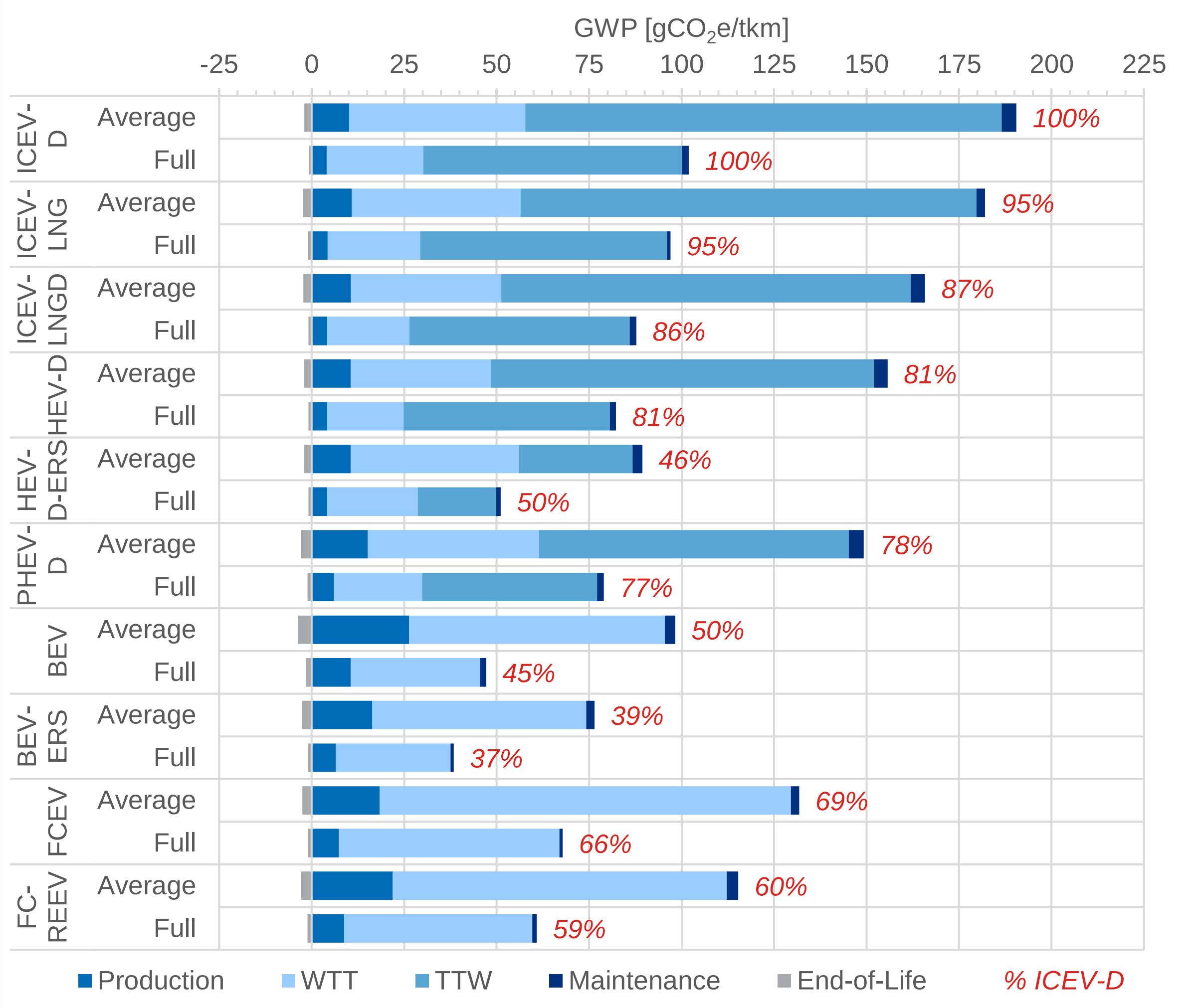
Vehicle loading assumptions can therefore have important effects on the extent of impacts from HDVs as a higher loading factor can increase the relative benefits of alternative powertrains if assessed on the basis of their activity (i.e. vkm) but become less significant if assessed on the basis of utility (in tkm).

Figure 5.79: Sensitivity on vehicle loading, Artic Lorry, Baseline Scenario, 2020. GWP per vehicle-km.



Notes: Results shown for the articulated lorry in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. % ICEV-D represents the impacts of a powertrain as a share of the impacts of the ICEV-D powertrain, for an average load, empty load and a full load. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 800,000 km over 10 years. 2020 BEV battery of 1370 kWh, with a 500km range on a long-haul cycle, and an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEV only.

Figure 5.80: Sensitivity on vehicle loading, Artic Lorry, Baseline Scenario, 2020. GWP per tonne-km.



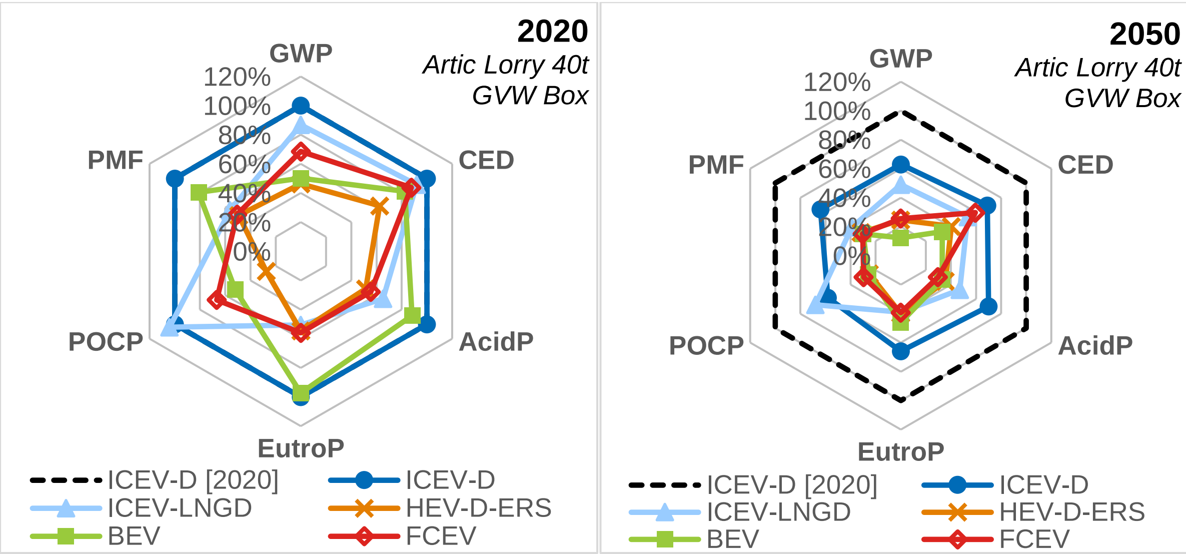
Notes: Results shown for the articulated lorry in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. % ICEV-D represents the impacts of a powertrain as a share of the impacts of the ICEV-D powertrain, for an average load and a full load. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 800,000 km over 10 years. 2020 BEV battery of 1370 kWh, with a 500km range on a long-haul cycle, and an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEV only.

5.5.6 Sensitivity on future tailpipe AQP reduction

This sensitivity explores potential future improvements to regulated air quality pollutant (AQP) emissions. Although there is no specific information on what future policy might look like in this area (i.e. post-Euro 6/VI), it is likely that there will be a tightening of existing limits in the future. An arbitrary 25% reduction per decade in all tailpipe AQP has therefore been modelled to illustrate potential impacts.

As Figure 5.81 shows, for articulated lorries, this reduction in AQP emissions results in significant improvements in 2050, across a number of impact categories to which these pollutants contribute. Similar effects are observed for other HDVs and LDVs. Despite the substantial reductions in AQP emissions achieved for diesel fuelled vehicles, xEV powertrains are still expected to outperform conventional powertrains across all categories in 2050. Gas-fuelled vehicles, on the other hand, perform similarly to xEVs by 2050 in all AQP mid-points, except for POCP.

Figure 5.81: Sensitivity on future tailpipe AQP reduction, Articulated Lorry, Baseline Scenario, 2020 and 2050



Notes: Results shown for the articulated lorry in the baseline scenario. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 800,000 km over 10 years. 2020 BEV battery of 1370 kWh, with a 500km range on a long-haul cycle, and an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEV only.

In the case of cars (not shown here), xEV powertrains show particularly significant benefits compared to diesel cars for POCP, EuroP and PMF impacts. For gasoline cars, the effects are similar (i.e. ICEV is still outperformed by xEVs) although they are less pronounced. Gas-fuelled vehicles, on the other hand, perform similarly to xEVs by 2050 in all AQP mid-points, except for POCP.

These results suggest that, although increasingly stringent limits on AQP emissions can lead to significant impact reductions for conventional vehicles across a range of impact categories, more substantial improvements would still be needed (mainly to tailpipe NO_x) to bring vehicles using ICE closer to xEVs.

5.5.7 Sensitivity on ambient temperature

This sensitivity explores the effects of full vehicle operation at very low or very high ambient temperatures. More extreme conditions will require significant use of auxiliary systems (for cabin heating or cooling) which have an impact on energy consumption and electric range. Their relative effects for different powertrains are analysed here to shed more light on the impacts on driving conditions in different climates.

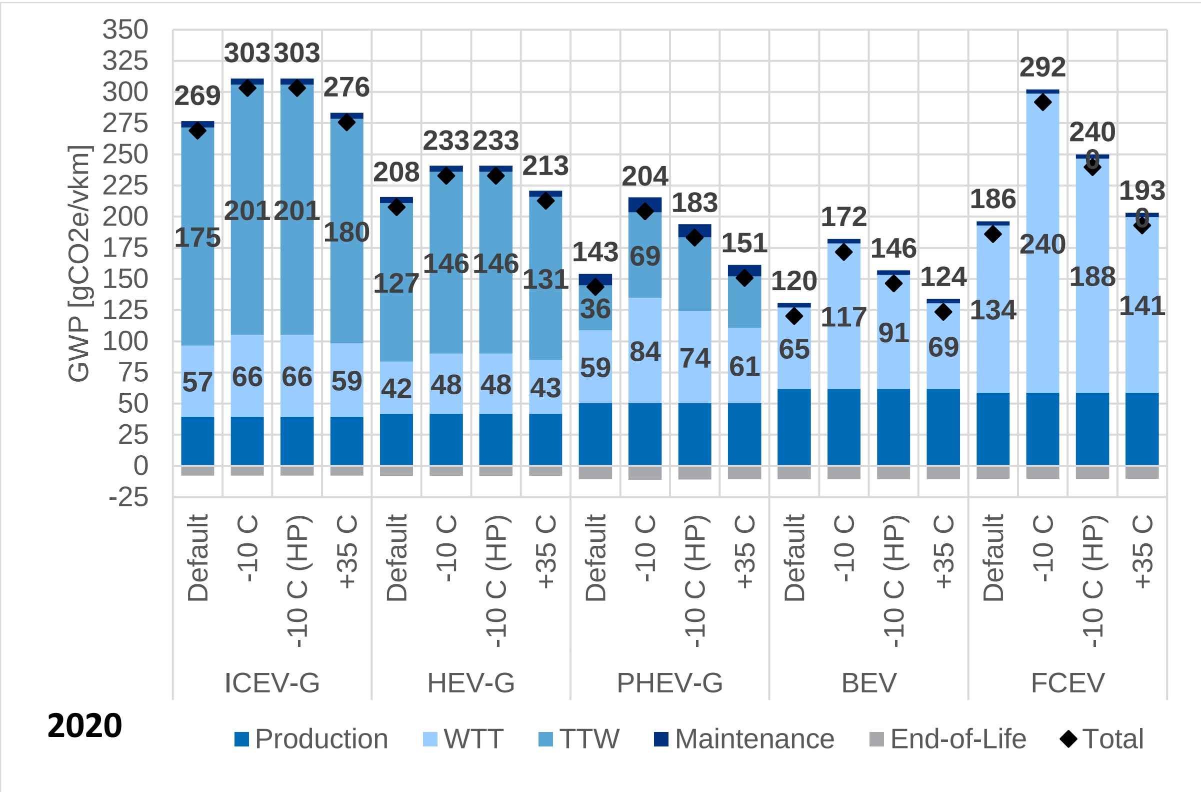
The default assumption in this study (20ºC), representing the regulatory test cycle average temperature, is compared to more extreme ambient temperatures of -10ºC and +35ºC. Effects at -10ºC have been considered for xEVs without and with a Heat Pump (HP), as this feature (present in most BEV models currently on the market) significantly reduces energy demand for heating. This sensitivity was only performed for LDVs as no data was available for HDVs.

Figure 5.82 shows that for a car, WTW impacts can increase significantly in colder conditions which require heating of the vehicle, especially for xEVs without a heat pump. Increases in WTW impacts are more modest for higher temperatures. As a result, when operating at very low ambient temperatures there is a relatively small closing of the gap between the impact for PHEVs/BEVs and other powertrains. Whilst the relative increase in electric energy consumption for BEVs without a heat pump can be quite significant, the absolute increase in GWP impact is still as significant as the increase in impact for conventionally fuelled, where the increase in energy consumption is smaller but their larger impact from their WTW stage means that the overall increase in impact is greater. For FCEVs however, the gap to the equivalent ICEV-G becomes much smaller, especially in cold conditions without a Heat Pump, as the relative increase in energy consumption and their WTW impacts are both large.

Over time, the effects of this sensitivity become smaller, especially for xEVs, due to electricity decarbonisation which reduces their WTW impacts. As a result, their relative performance, and in particular that of the BEV, remains largely unchanged.

This sensitivity therefore demonstrates that climate conditions can significantly determine the performance of xEVs however their relative impacts (compared to the conventional powertrain) are not highly affected, except in the case of FCEVs in 2020. Future reductions in impacts from their WTW stage minimise the effects of this sensitivity for all xEVs.

Figure 5.82: Sensitivity on ambient temperature, Lower Medium Car, Baseline Scenario, 2020



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.8 Sensitivity on fuel production chain methodology

Earlier Section 5.3.2 presented and discussed results for different fuel production chains and how varying certain methodological options/choices (principally allocation, counterfactuals and land-use change) can significantly influence the overall results for certain individual fuel chains.

As detailed in earlier sections, the methodology developed throughout this study included the use of substitution for multi-functionality (all fuels except primary fossil fuels), impacts from counterfactuals (secondary fossil and biogenic fuels) and land-use change emissions (primary biogenic fuels). The resulting WTT impacts did not, however, allow for a like-for-like comparison of fuels and vehicles, primarily due to variability in data robustness. Additional WTT results were therefore modelled as the default assumption for the overall vehicle LCA using energy allocation without a counterfactual scenario for secondary/waste-derived feedstocks, as this is closest to the current regulatory situation in the European Union. Estimates for land-use-change (LUC) impacts, which also takes soil organic carbon (SOC) emissions into account, are included by default.

This sensitivity explores the effects of these methodological choices on the overall vehicle LCA GWP impacts for four alternative cases (shown in Figure 5.83 and Figure 5.84 below):

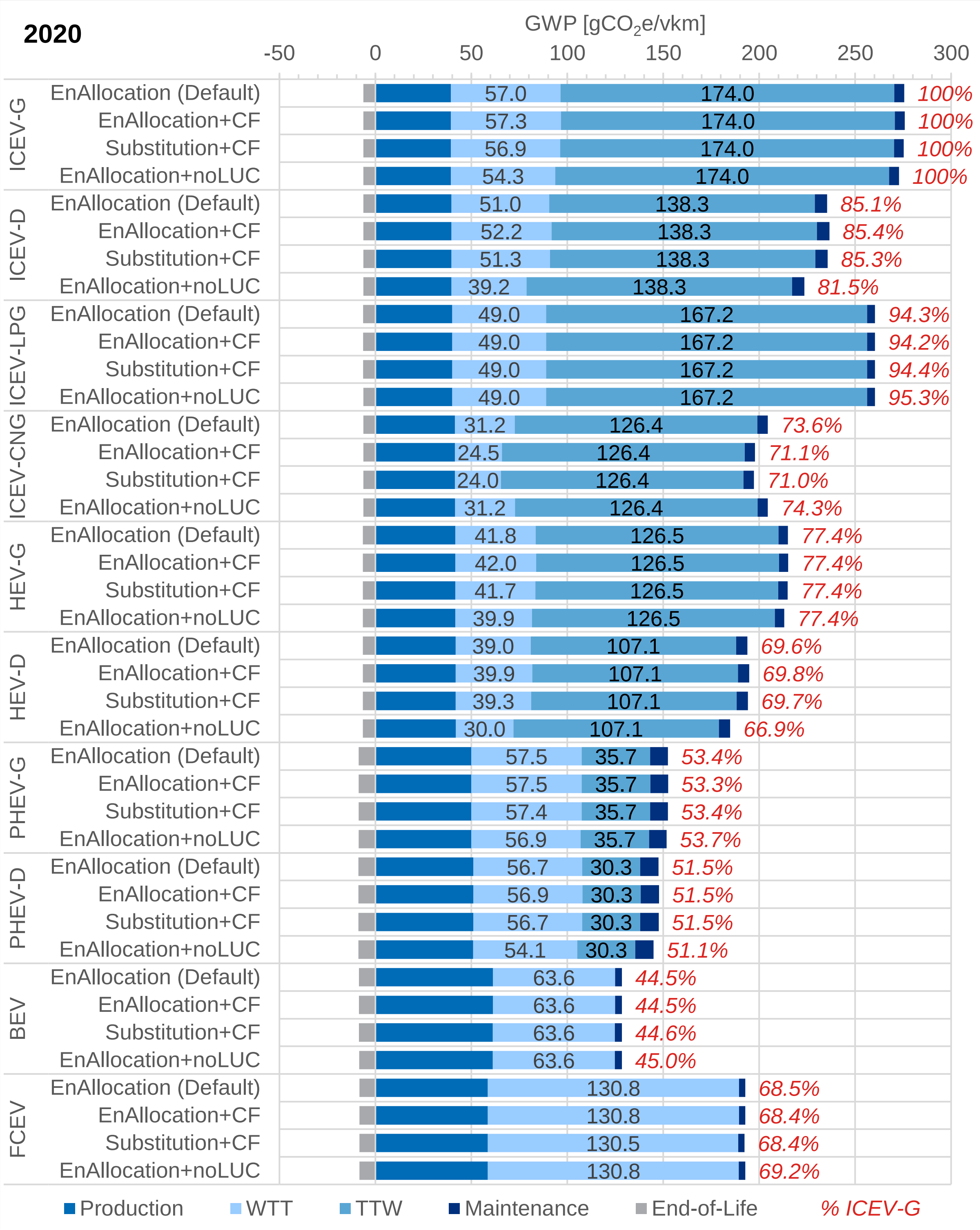
1. **EnAllocation** (energy allocation, with no counterfactual scenario, *with* land-use change emissions, Default): Allocation of impacts on an energy content basis where processing co-products are produced, with *NO* counterfactual scenario for secondary/waste-derived feedstocks.
2. **EnAllocation+CF** (energy allocation + counterfactual scenario, *with* LUC emissions): Allocation of impacts on an energy content basis where processing co-products are produced, *WITH* a counterfactual scenario included for secondary/waste-derived feedstocks
3. **Substitution+CF** (allocation by substitution + counterfactual scenario, *with* LUC emissions): Allocation of impacts using substitution where processing co-products are produced*, *WITH* a counterfactual scenario included for waste-derived feedstocks. *For conventional fossil fuel components, the methodology applied is always energy allocation only (as this is the output format from the ifeu refinery model used for calculating the impacts from such fuels).
4. **EnAllocation+NoLUC** (energy allocation, LUC impacts *excluded*). Allocation of impacts on an energy content basis where processing co-products are produced, with *NO* counterfactual scenario for secondary/waste-derived feedstocks, and excluding LUC impacts.

Figure 5.83 (for 2020) and Figure 5.84 (for 2050) show the relative WTW impacts (by powertrain type) from the production of fuels and electricity for the defined scenario fuel/electricity mix for the Tech1.5 scenario (see 4.7.4 for the fuel blends and for the electricity generation mix). The figures show that in many cases only marginal changes in the relative performance of different powertrain types, and some differences between the 2020 and 2050 results (where in the latter case there are higher levels of substitution of low carbon fuels – see earlier Figure 4.11).

For the 2020 situation (Figure 5.83), changing the allocation and counterfactual methodological options has relatively small impacts on the results for liquid fuels. However, this has a more significant impact on gas-fuelled vehicles (i.e. ICEV-CNG) which use a larger share of fuels derived from secondary feedstocks where the counterfactual results in lower impacts. The exclusion for LUC impacts has a relatively smaller impact on gasoline-type fuel chains, but more significant impacts on the diesel-type fuel chains, where there is currently a significant share of higher LUC impact feedstocks (i.e. particularly palm oil and to a lower extent rapeseed). Excluding counterfactual and land-use change impacts reduces the WTT impacts of the blended diesel fuels by ~20% compared to the Default. The overall comparison of ICEVs with xEVs does not change meaningfully for GWP impacts.

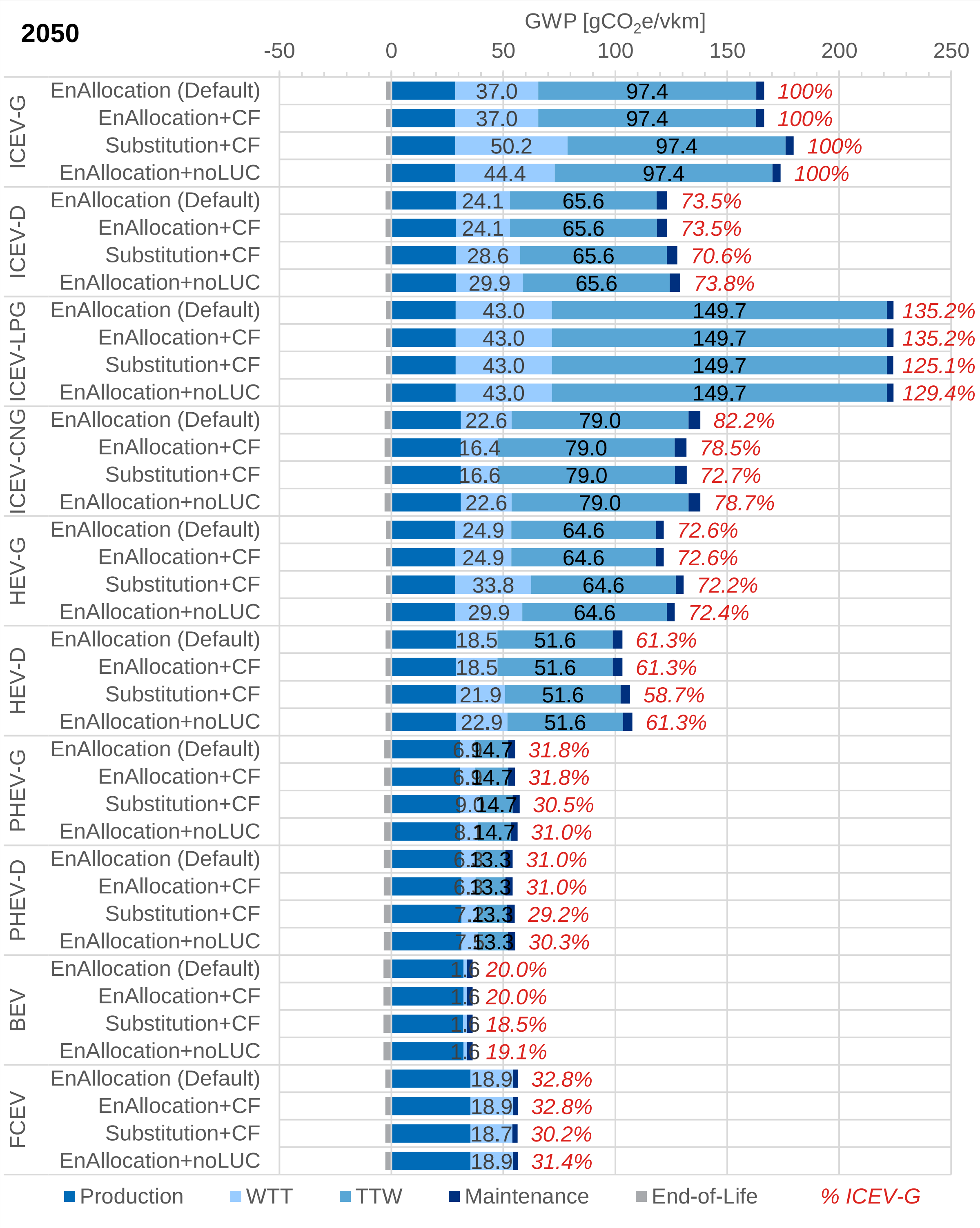
For the 2050 situation (Figure 5.84), the larger shares of bio- and synthetic-fuels blended with conventional fossil fuels in the scenario results in more substantial impacts when switching to different methodological options, with increased WTT impacts resulting from substitution and counterfactual inclusion for the liquid fuels, and decreased impacts (due to larger shares of secondary feedstocks) for CNG blend/gas-fuelled vehicles. By 2050, it is assumed the highest LUC fuels (e.g. produced from palm oil) are phased out of the fuel used in vehicles, and higher shares of substitution of synthetic fuels derived from wastes and SRC in liquid fuel blends (with the latter having negative LUC GWP impacts). In contrast to the situation for 2020, excluding GWP impacts of LUC results in an increase (worsening) of net impacts for the WTT stage for liquid fuels. Again, the overall comparison of ICEVs with xEVs does not change meaningfully for GWP impacts.

Figure 5.83: Breakdown of lifecycle GWP impacts by fuel production LCA methodology, Lower Medium Car, Tech1.5 Scenario, 2020



Notes: Results shown for the lower medium car in the Tech1.5 scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years; 2020 BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

Figure 5.84: Breakdown of lifecycle GWP impacts by fuel production LCA methodology, Lower Medium Car, Tech1.5 Scenario, 2050



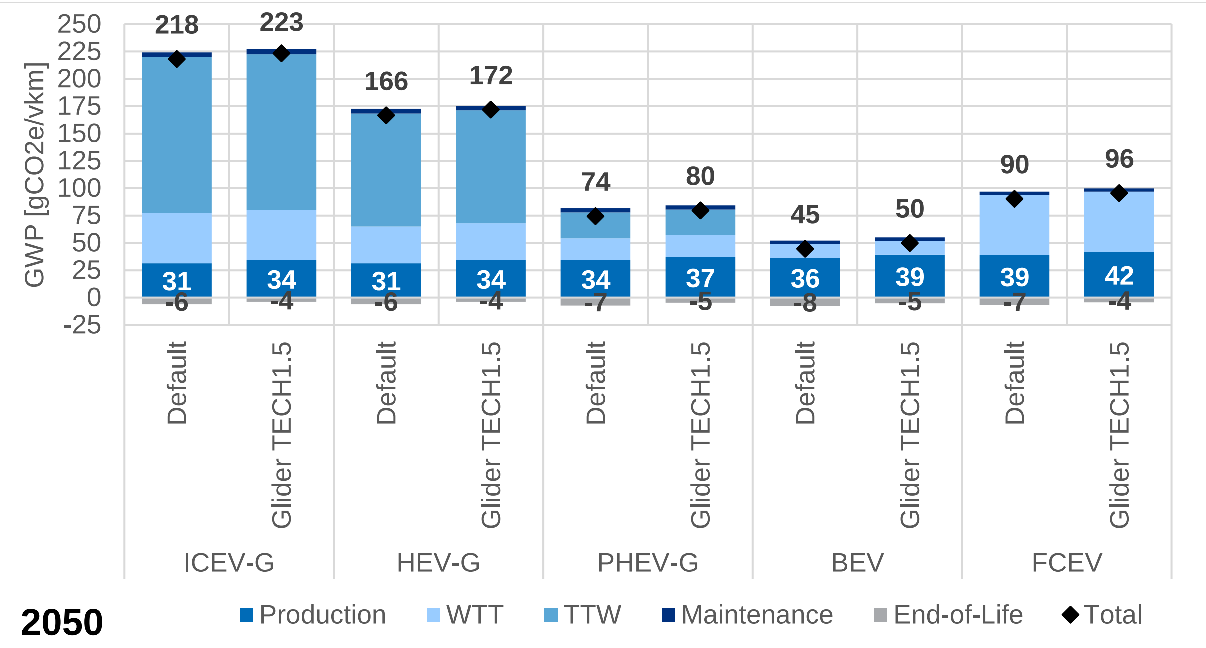
Notes: Results shown for the lower medium car in the Tech1.5 scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years; 2050 BEV battery of 74 kWh, with 600km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.9 Sensitivity on the material composition of the glider

This sensitivity illustrates the effects of variations in the material composition of the glider. The substitution of materials in the glider for more lightweight materials (e.g. plastic, aluminium and carbon fibre reinforced plastic) is a strategy that manufactures have at their disposal to reduce overall vehicle mass and therefore the (regulated) tailpipe CO_2 emissions from their vehicles. Lightweight materials however can have significantly higher embedded impacts compared to those that they replace (such as iron and steel) associated to a more energy-intensive production of the former. The recycling of these materials can also be more difficult and, therefore, benefits in the EoL stage can be smaller. This sensitivity can therefore help shed light on the extent to which the use of more lightweight materials can lead to higher impacts in isolation, that is, independent of effects on energy consumption. This is only a theoretical case where the effects of substituting materials in the glider are assessed but their impacts in terms of mass reduction on energy consumption are not considered.

For this sensitivity, the material composition of the glider in the baseline scenario is compared to the material composition in the TECH 1.5 scenario where higher shares of plastic, aluminium and eventually carbon fibre reinforced plastic are assumed for 2030-2050[29] (Figure 5.86). Figure 5.85 shows that overall effects (on production and EoL recycling/disposal) on GWP impacts in 2050 for a lower medium car are relatively modest. Similar effects are also found across other vehicle types and for different mid-point indicators.

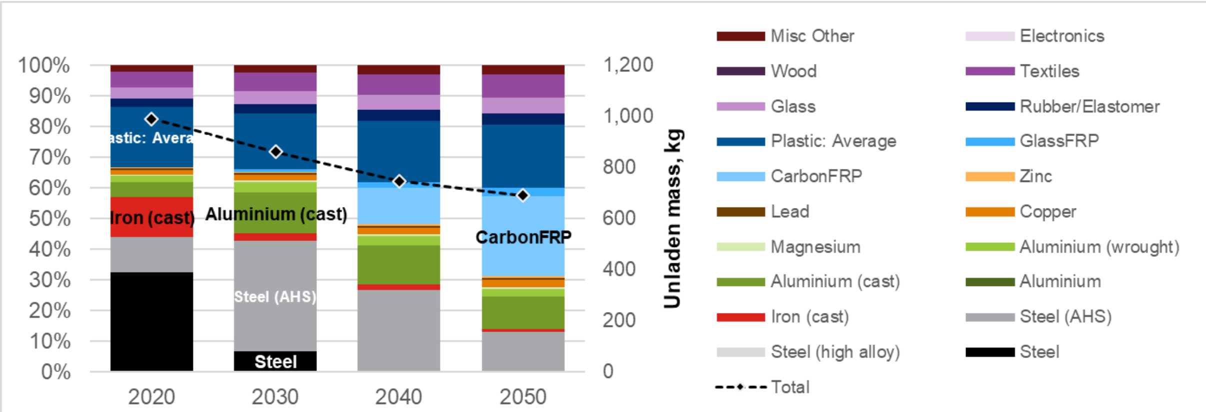
Figure 5.85: Glider Material Composition, Lower Medium Car, Baseline Scenario, 2050



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2050 BEV battery of 74 kWh, with 600km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

[29] Both scenarios assume an increasing degree of lightweighting over time but the rate at which this takes place is higher in the TECH1.5 scenario.

Figure 5.86: Material composition of the glider of a lower medium car in the TECH 1.5 scenario, 2020 - 2050



5.5.10 Sensitivity on the electric range of xEVs

This sensitivity explores variations in the electric range of PHEVs and BEVs, and therefore the capacity/mass of the traction battery required for these vehicles (i.e. for a fixed/given battery energy density). It is intended to investigate the extent of their effects on the LCA results in light of uncertainties around real world electric range and potential for further increases in driving ranges.

There are two main effects at play here: electric range is inherently linked to battery size and therefore a variation in the former parameter affects both impacts from the production stage and impacts from energy consumption in the WTW stage. If everything else is constant, a larger battery would be required to improve range, leading to higher manufacturing impacts. In addition, a larger battery would also add extra weight to the vehicle and therefore result in higher energy consumption during the use phase. Figure 5.87 shows the variation in the assumptions on electric range for both the PHEV and the BEV tested in this sensitivity analysis (in addition to the default values assumed in this study).

Figure 5.87: Assumptions on WLTP electric range for PHEV and BEV

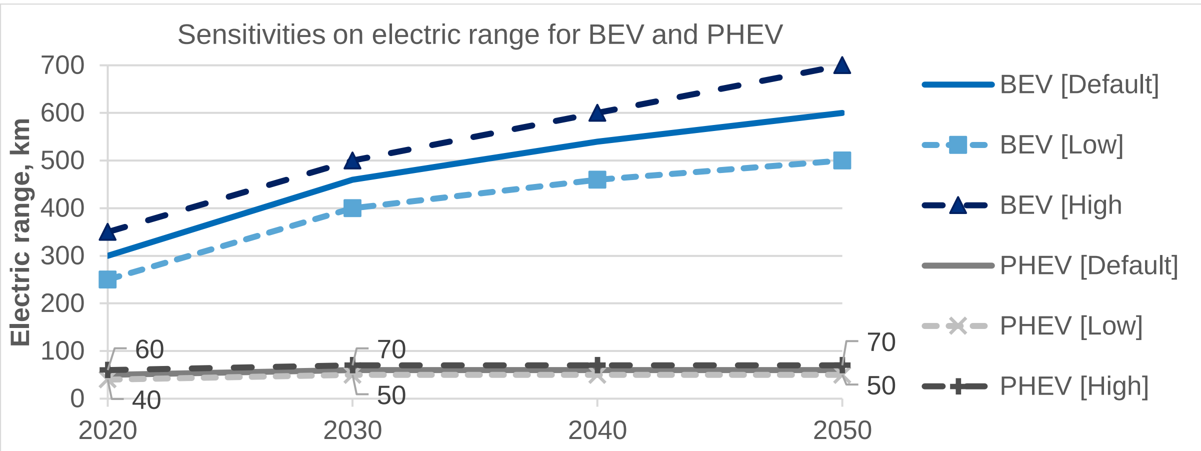


Figure 5.88 illustrates the effects of this sensitivity on the GWP impacts for a car in 2020. Two opposite effects can be observed for the PHEV and the BEV:

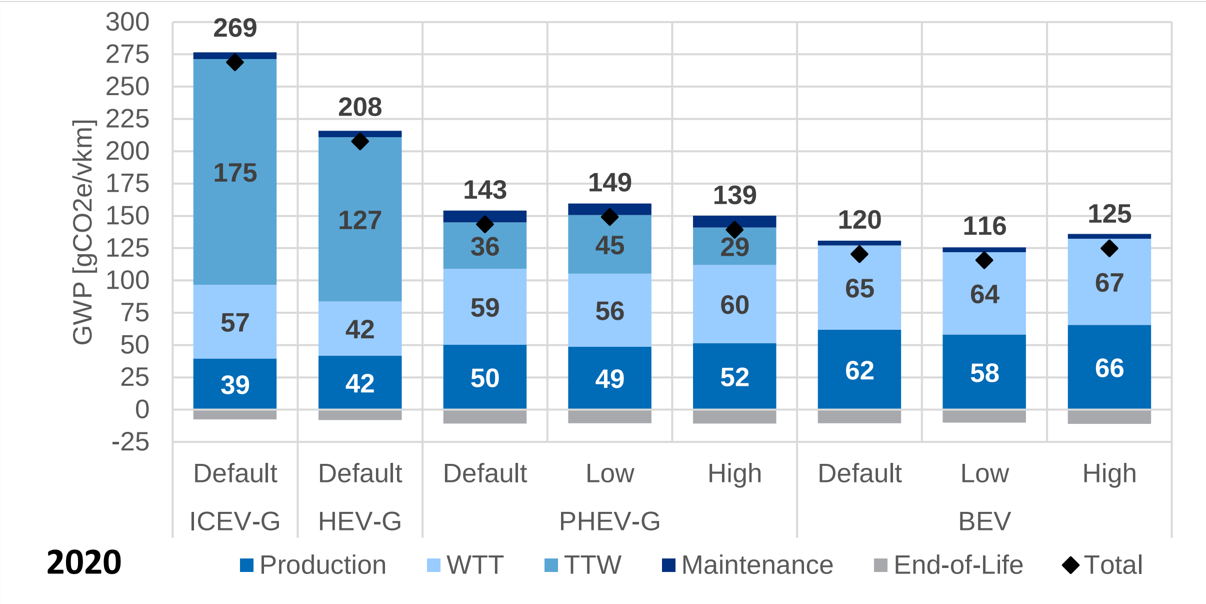
- The results show that a longer range (represented by the high variant in the figure) reduces the overall impacts from the PHEV due to the higher share of electric driving which decreases impacts from the TTW stage (but increases WTT impacts). Since the ICE driving is more GWP intensive than electric driving, shifting to more electric driving leads to an overall reduction in WTW impacts. This effect is also sufficiently large to compensate for the increase in the impacts from the production stage associated with the use of a larger battery;
- On the other hand, a longer range increases the impacts from the BEV mainly due to higher manufacturing emissions associated with a larger battery.

For both cases, however, the effects of this sensitivity are relatively modest. Over time, as the impacts from the production stage of the BEV are expected to decrease, the effects of this sensitivity also diminish in future years for this powertrain. For PHEVs, on the other hand, the effects of this sensitivity become slightly more significant as the benefits from electric driving increase with the decarbonisation of electricity and manufacturing impacts become smaller.

For HDVs, this sensitivity has a smaller effect for the PHEV, whilst the effect on the BEV can become more pronounced. It is expected that for these vehicles changes in the electric range affect the size of the battery more significantly resulting in more substantial impacts on the manufacturing and on WTW stages.

It can therefore be concluded that increasing the electric range for PHEVs can increase their net benefits, whilst the opposite occurs for BEVs which demonstrate lower impacts for smaller ranges. At the same time, this sensitivity also demonstrates that the variation in results is moderate and becomes even smaller for BEVs in future periods, where an increase in range and battery size is associated with a smaller increase in GWP impacts.

Figure 5.88: Sensitivity on xEV Electric Range, Lower Medium Car, Baseline Scenario, 2020



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 default BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.11 Sensitivity on energy density of batteries

This sensitivity considers different rates for improvement of battery energy density in future years due to a combination of changes in chemistry, cell and pack improvement. Technology in this area is rapidly evolving but the rate of development and eventual uptake is still uncertain. Varying assumptions were therefore tested to account for this uncertainty and understand the effects of potential future developments with resulting improvements in battery density.

The trajectories for improvements in energy density of batteries up to 2050 are shown in Figure 5.89. Their effects on the GWP impacts for a car in 2030 are shown in Figure 5.90. Overall, the effects of this sensitivity on GWP impacts are relatively low per vkm, however they are more significant for resource depletion and human toxicity impacts. In future periods, these effects become even less pronounced given that the impacts associated with the production of batteries are expected to decrease over time (i.e. lower impacts per kWh battery). The overall effects of this sensitivity are similar in some respects to the earlier sensitivity on electric range (i.e. in increasing/decreasing impacts from battery manufacturing), however without the resulting feedback on average share of electric km travelled for PHEV powertrains that also affects the overall result.

Similar effects are found for other vehicle types, except in the case of articulated lorries where benefits from higher energy density in terms of longer ranges and higher load capacity lead to slightly more significant effects from this sensitivity.

This sensitivity therefore reveals that uncertainty around the trajectory for improvements in energy density are not likely to lead to significant differences in the LCA results, although these can be more important for certain vehicle types.

Figure 5.89: Battery pack energy density projections

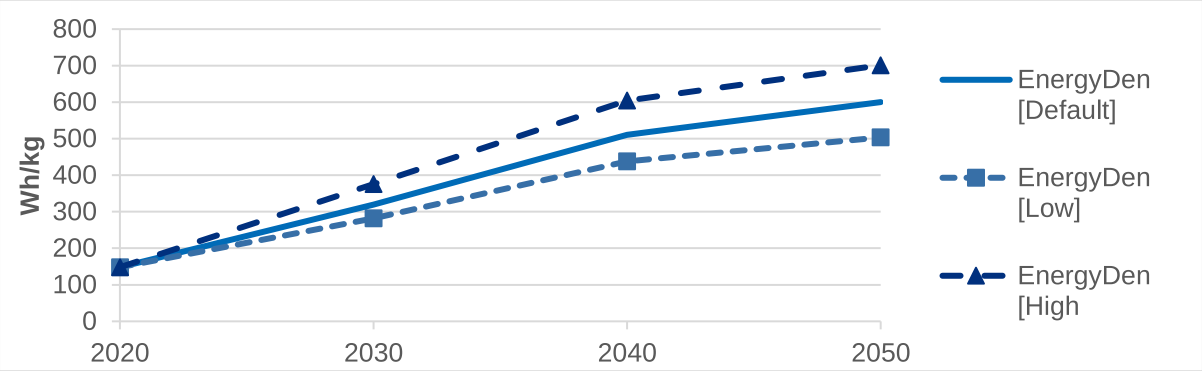
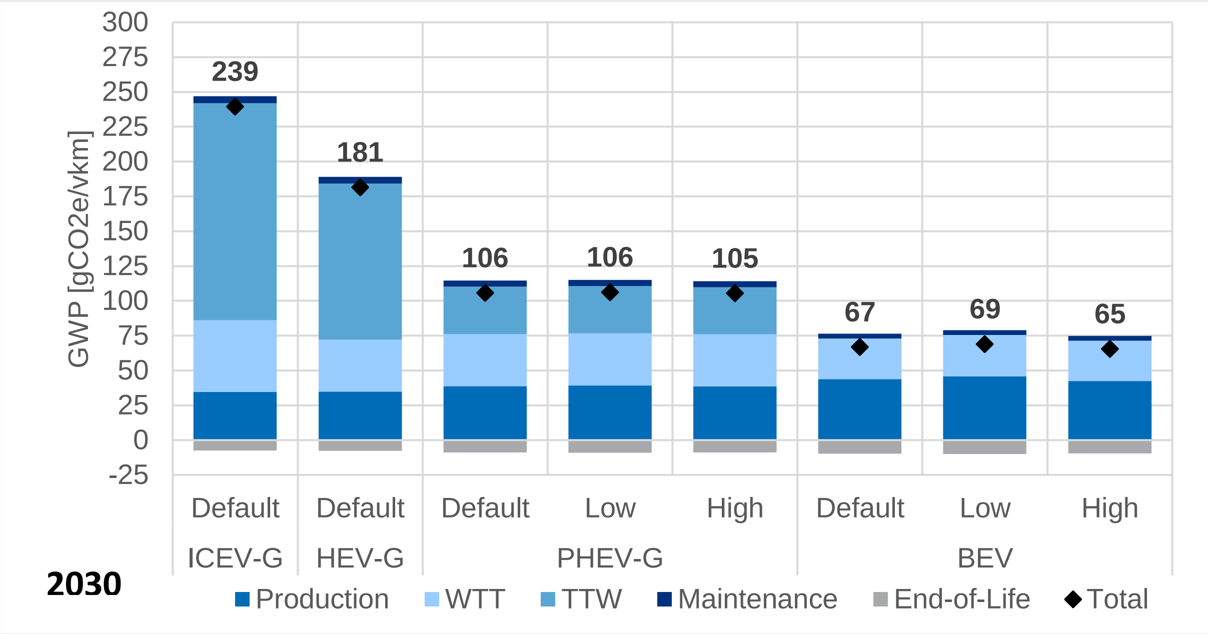


Figure 5.90:Sensitivity on energy density of batteries, Lower Medium Car, 2030



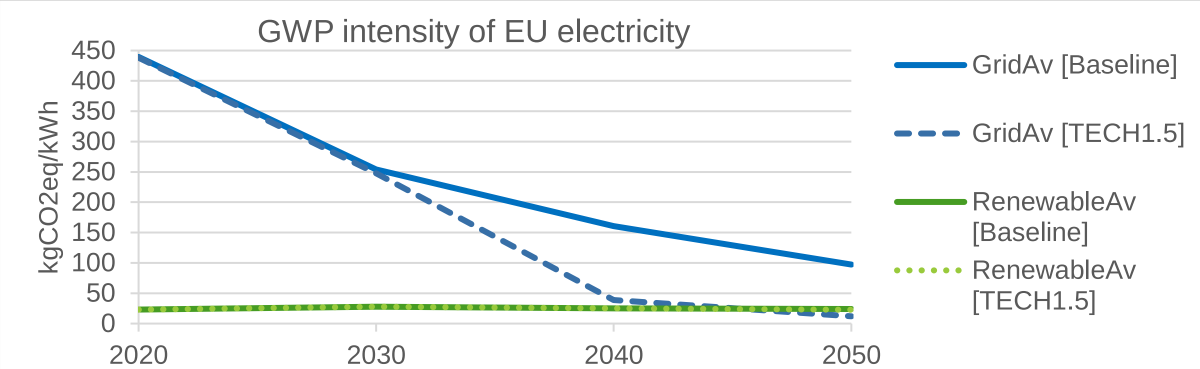
Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 default BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.12 Sensitivity on battery production and EoL

This sensitivity is intended to assess the effects of an alternative scenario where an EU sustainable value chain for battery production and EoL is established, meaning that:

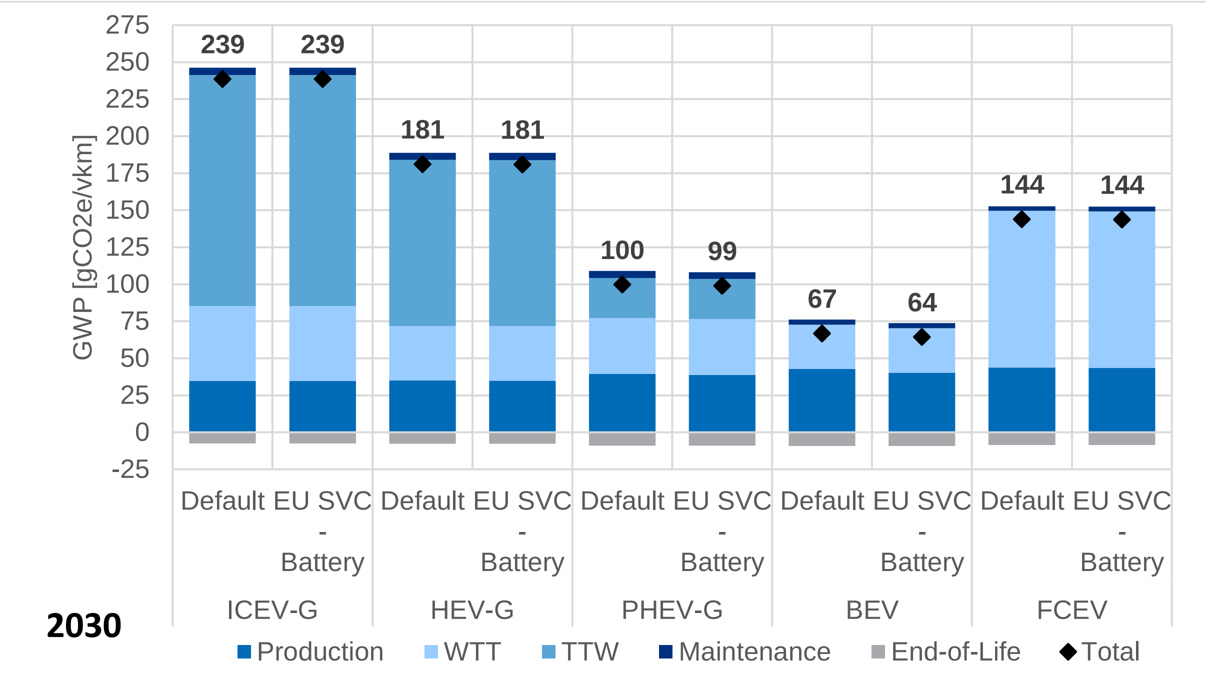
- Renewable electricity is used for manufacturing and end-of-life processes (see assumptions considered for the GWP intensity of electricity in Figure 5.91)
- Higher recycling rates of batteries are assumed
- Higher share of EU-based manufacturing is also assumed

Figure 5.91: Assumptions on GWP intensity of EU electricity



As Figure 5.92 illustrates for a car in 2030, effects on the GWP impacts are relatively low per vkm across all powertrains considered. The effects become more significant for other impact categories including resource depletion and human toxicity due to the increase in key recovered materials, such as copper.

Figure 5.92:Sensitivity on battery production and EoL, Lower Medium Car, Baseline Scenario, 2030



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 default BEV battery of 58 kWh, with 300km WLTP range; an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

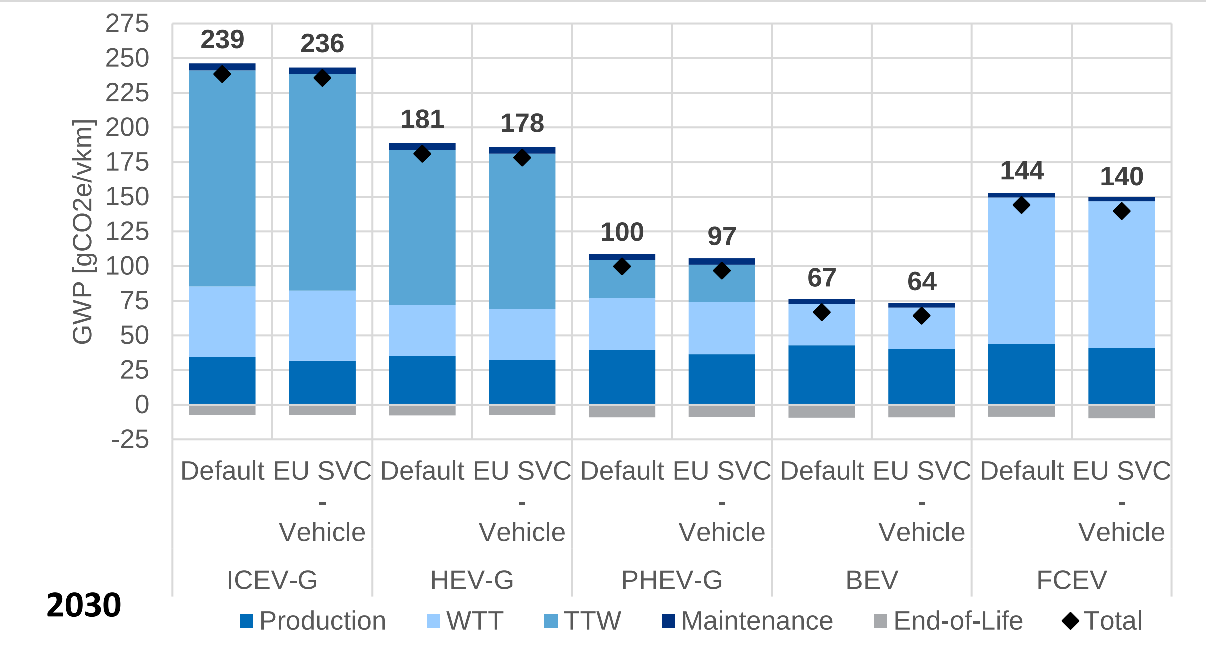
5.5.13 Sensitivity on vehicle production and EoL (excluding batteries)

Similar to the sensitivity discussed above, this sensitivity explores the effects on the results from an EU sustainable value chain for vehicle production and EoL (excluding the battery) based on the following assumptions:

- Renewable electricity is used for manufacturing and end-of-life processes (see assumptions considered for the GWP intensity of electricity in Figure 5.91 above)
- Higher recycling rates

For this sensitivity, the effects on GWP impacts are also relatively low per vkm (Figure 5.93). In future periods, effects diminish to an extent as the grid electricity assumed in the default case decarbonises.

Figure 5.93: Sensitivity on vehicle production and EoL (excluding batteries), Lower Medium Car, Baseline Scenario, 2030



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 default BEV battery 58 kWh, with 300km WLTP range; average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.14 Sensitivity on second life applications of batteries

This sensitivity considers the effects of a high share of xEV batteries going to second life applications. As highlighted in the literature, the use of battery second life applications is still in its early stages and more research is required. To account for this uncertainty, a low share is assumed in this study but the potential for a higher use in future periods is tested by this sensitivity analysis (Figure 5.94).

Figure 5.95 shows that the effects on GWP impacts are relatively low per vkm for a car in 2030. In future periods, the effects become even smaller as batteries which are replaced had a lower impact associated with their manufacture, and therefore the credit applied for their re-purpose is also lower. However, the reduction in impacts for resource depletion and human toxicity are more significant.

Figure 5.94: Assumed shares of battery repurposing for second-life

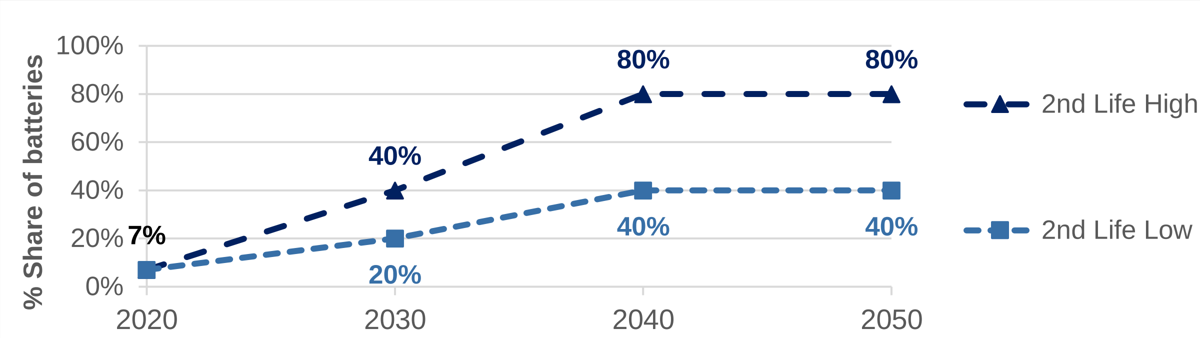
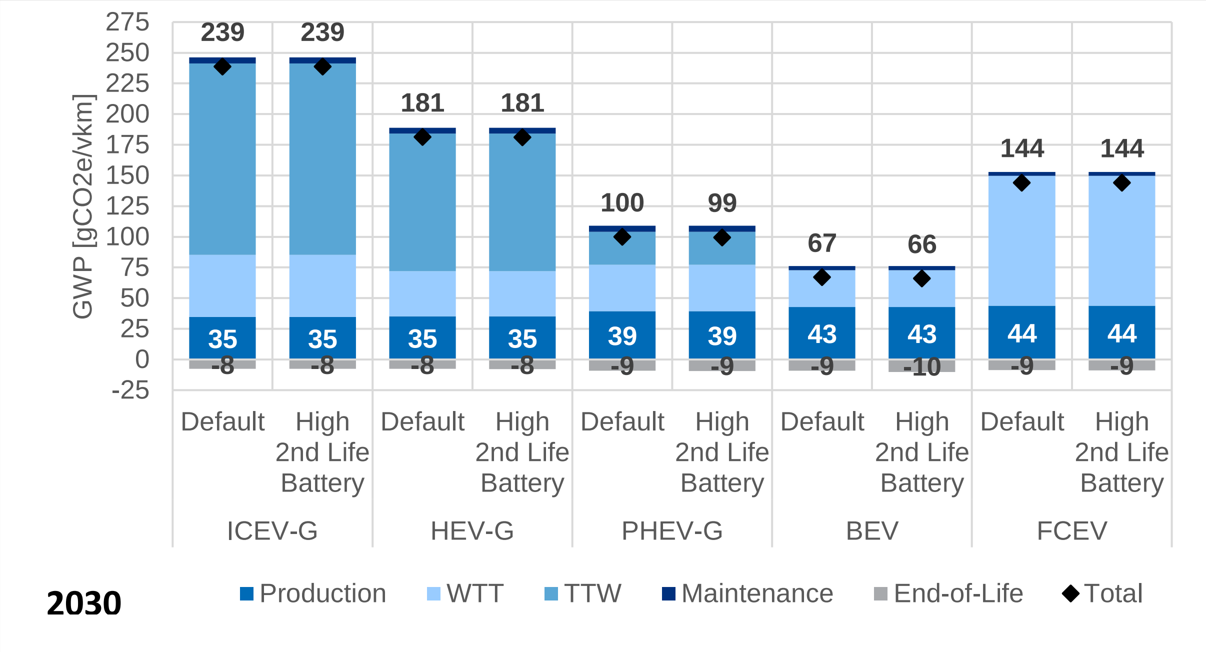


Figure 5.95: Sensitivity on second life applications of batteries, Lower Medium Car, Baseline Scenario



Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 default BEV battery 58 kWh, with 300km WLTP range; average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for xEVs.

5.5.15 Sensitivity on battery manufacturing energy consumption

One of the most significant input assumptions affecting the calculation of impacts from battery manufacturing is the energy consumption used in this manufacturing and its source. Two key datasets were identified for the assumptions in this area for the current situation, (i) those used in the GREET model (ANL, 2018), and the default values provided in the draft PEF Category Rules (PEFCR) for rechargeable batteries for mobile applications (RECHARGE, 2018). These inputs are summarised in Table 5.5 below, by battery manufacturing sub-stage. The main differences relate to the assumptions on the source of energy used to provide heat for dry room conditions and for drying/solvent removal/recapture, which are the most energy intensive parts of battery manufacturing. The data used in the GREET model (which is also used as the basis for most of the other battery manufacturing and end-of-life calculations in our vehicle LCA model) is based on information from a major Chinese battery manufacturer, which uses natural gas to provide this heat (which is generally much lower cost and also lower impact except for electricity mixes with high shares of renewables). The dataset from PEFCR assumes all manufacturing energy is provided by electricity; at this point it is only known that Tesla uses

100% electricity in its battery manufacturing in Nevada (USA), and also for the proposed Northvolt Gigafactory in Sweden (Kurland, 2019). Since there is no clear information on the use of either natural gas or electricity to provide heat in battery manufacturing used to supply the EU vehicle market, a conservative nominal 50:50 blend of these input data as a default in our calculations.

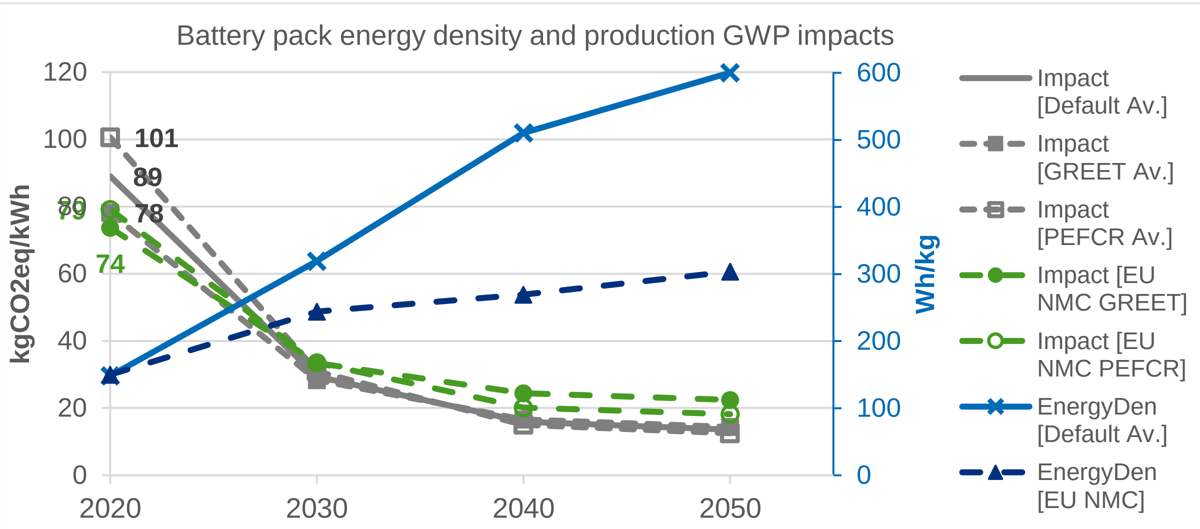
The following Figure 5.96 provides a summary of a sensitivity on the intermediate battery manufacturing impact calculation results from the vehicle LCA modelling, using alternative assumptions for (a) the average mix of battery chemistries and regional manufacturing (i.e. principally affecting the electricity mix), (b) results for manufacturing of NMC li-ion battery chemistries using the EU-average electricity mix. The results show a range of values between 78 gCO_2e/kWh (for GREET energy consumption) and 101 gCO_2e/kWh (using PEFCR energy consumption) for the average battery supply mix in 2020, and from 74 to 79 gCO_2e/kWh for NMC battery manufacturing using GREET or PEFCR data respectively and the EU average electricity mix. (Note, assuming 100% renewable energy results in ~66.5 / 48.5 / 57 gCO_2e/kWh using GREET / PEFCR / Default energy consumption assumptions, respectively, for manufacturing of NMC batteries in the EU).

These results are slightly higher than those calculated for EU production NMC chemistry lithium-ion batteries based on PEFCR data by (IVL, 2019) of 77 $kgCO_2e/kWh$ and those calculated using GREET for 'an EU-dominant supply chain' by Argonne National Laboratory researchers (Kelly, Dai, & Wang, 2019) of 65 $kgCO_2e/kWh$ (with equivalent results produced via a 'Chinese-dominant supply chain' of 100 $kgCO_2e/kWh$). However, we have assumed a slightly higher share of steel used in battery pack packaging versus GREET in 2020 based on a review of what typically used in BEVs currently on the market. These sources will have also used different assumptions also for the materials used in battery manufacturing (and where these were sourced from), which may help explain the differentials from the calculation in our vehicle LCA modelling.

Figure 5.96 below also shows that the results of the sensitivities narrow significantly by 2030, as the GHG intensity of (average grid) electricity used in battery manufacturing is projected to reduce significantly, so that the impacts are more similar for manufacturing heat provided by gas or electricity. In future periods, it is also assumed that there is a shift away from using gas, to using electricity also as a consequence of this shift (and an anticipated shift to minimise the impacts of battery manufacturing).

Further information on the assumptions used in the calculation of impacts from battery manufacturing are provided in earlier Section 4.7.3, and in Appendix A4.3.2.1 of this report.

Figure 5.96: Sensitivity on battery manufacturing energy source on GWP impacts of battery manufacturing, Baseline Scenario



Notes: 'Av.' assumes default current average mix of battery chemistries, and average mix of regional battery manufacturing; this is the default methodology/basis for the calculations shown in the rest of the report. 'EU NMC' assumes current mix of NMC chemistries only and 100% EU manufacturing using the current EU average electricity mix. This is provided also to provide an illustration of the differential between our main 'market average' and a pure NMC chemistry-based analysis.

Table 5.5: Summary of energy consumption assumptions for battery manufacturing

Battery Area	Energy Source	Unit	GREET	PEFCR	Default*
Periphery/pack manufacturing	Electricity	MJ/kg battery		0.001	0.001
Cell manufacturing	Electricity	MJ/kg battery	4.275	41.200	11.635
	Natural Gas	MJ/kg battery	20.015		10.008
Cathode material manufacturing	Electricity	MJ/kg battery	5.040		13.622
	Natural Gas	MJ/kg battery	23.355		11.677
Total	All	kWh/kWh battery	**102**	**80**	**91**

Notes: * Default assumptions used in the vehicle LCA modelling, based on a 50:50 average of energy consumption from GREET and PEFCR assumptions, with PEFCR electricity consumption distributed between battery cell and cathode material manufacturing based on a similar ratio of natural gas use between these two areas in GREET.

5.6 Summary of uncertainties and limitations for the analysis

LCA is inherently imprecise/uncertain: uncertainty affects both input data and computational steps subject to methodological choices. The broad scope of the study has also led to trade-offs with level of detail and accuracy in certain areas. A summary of some of the key high-level uncertainties and limitations is provided below, with further discussion provided in the preceding sections.

In all cases, and common with LCA studies overall, the results presented should be viewed as having uncertainties associated with them, and **results should not be taken as absolute values/comparisons**, for the reasons summarised below. Sensitivity analysis has been performed on some of the most important assumptions and parameters affecting the overall results to help illustrate how they affect the relative performance of different vehicle types, and therefore how much some of the results might be expected to vary depending on the specific situation (in terms of the vehicle specification, use and end-of-life treatment aspects):

- The overall results are produced for generic vehicle types, which provides a good basis for further policy discussions, however:
  - The validity of the results for specific single vehicle models will be very significantly influenced by their specific design, specifications and performance.
  - Comparison with more novel fuels/blends needs improved data/methodologies.
- Considerably less data/literature is available for certain vehicle types (mainly lorries and buses) and powertrains/fuels (especially e-fuels and alternative fossil fuels), and this may lead to higher uncertainties for these vehicles/energy types.
- The broad scope of considered environmental impacts leads to differences in data robustness between these impacts due to data uncertainties and asymmetries. Care should be taken in interpreting results, especially for less common/established impacts.
- Some key areas relating to the scope/boundary and the LCA methodology are subject to greater debate and could be further investigated, in particular:
  1. The extent and application of consequential modelling (particularly for the fuel production chains) including the use of counterfactuals for secondary/waste-derived fuels, and the allocation methodology (e.g. substitution versus allocation by energy).
  2. The end-of-life-modelling methodologies, assumptions and underlying datasets.
  3. The relevance of charging/refuelling infrastructure, which was excluded from the scope of this project. As mentioned in earlier Section 3.1.3, infrastructure impacts are likely to be more significant for powertrains using electric road systems (ERS). However, charging and refuelling infrastructure could also potentially be relevant in a comparative assessment of other alternative powertrains (e.g. residential/public slow and rapid charging; hydrogen refuelling stations, etc.).

5.6.1 Summary of data gaps and methodological simplifications for the vehicle chain analysis

This subsection provides a summary of some of the data gaps and simplifications from the overall lifecycle impact analysis for the different stages, summarised in Table 5.6 below. Most of these data gaps and simplifications are not expected to have a marked impact on the overall results of the LCA, other than to improve the precision of estimates. Where more significant effects might be expected, these have been highlighted in the text.

Table 5.6: Summary of data gaps and simplifications for the vehicle chain analysis

Stage	Data gaps and simplifications/limitations and uncertainties
Vehicle specification	• The impacts of high/low ambient temperature conditions on energy consumption have been assessed using a simplified methodology for LDVs, which should capture the major effects here. However equivalent data is not available for HDVs. Impacts are likely to be significant for buses and coaches (due to high HVAC loads), and relatively lower for lorries (which have lower auxiliary requirements), though unlikely to fundamentally change conclusions on the attractiveness of different powertrains. • No information was available on the potential differences between real-world energy consumption for HDVs and the values derived using the EC's certification tool (VECTO). Estimates for real-world energy consumption are currently based upon the variation in reported real-world mileage shares for urban/rural/motorway roads vs the relevant VECTO test-cycles for HDVs (i.e. accounting for the different average MJ/km on different road types/speeds).
Vehicle manufacturing	• For certain, mostly less significant, materials there was no data on the impacts for producing secondary/recycled material in the background LCI database (Ecoinvent) and so gaps were filled mainly using assumptions for similar materials using the relative impacts of primary vs secondary materials. The most significant secondary material data gap was for carbon fibre reinforced plastic (CarbonFRP) – currently used in FCEV H_2 storage vessels and also anticipated to have greater use in the longer-term to reduce vehicle weight; in this case estimates were based on reported GHG and energy benefits from the literature for the recycled material. • The impacts of location/component-specific logistics are currently not captured; however, these are very unlikely to significantly affect the overall comparison of powertrains. • The impacts of component-specific manufacturing impacts (i.e. material/energy use, emissions and waste from manufacturing individual components) are not captured (other than general impacts for manufacturing of steel or aluminium components). • The impacts of manufacturing of new/future battery chemistries are highly uncertain, and currently modelled only at a high-level based on available research data.
Vehicle operation and maintenance	• No estimates were available on the potential future improvement to emissions of regulated pollutant emissions beyond those achieved by vehicles meeting the most stringent Euro standards (i.e. Euro 6d for LDVs and Euro VI for HDVs). Therefore these were set by default as unchanged in future periods for all vehicle types, and the impacts of potential improvements explored only through a simple sensitivity (see later Section 5.5.6). This **could have a significant impact** on the comparison of certain powertrains in the future, if more significant emission reductions are achieved. • Some powertrain-specific impacts of other maintenance / part replacements are not currently captured in the analysis. For example, replacement requirements for brake pads / discs, etc. are likely to be lower for powertrains using regenerative braking. • The general impacts from vehicle servicing (other than certain replacement parts and consumables) are not captured. Adding these would be expected to increase the overall impacts to a limited extent. Some EV manufacturers are now specifying longer recommended periods between servicing for BEVs (versus other vehicle types), which would likely to result in lower impacts in this area also.

Stage	Data gaps and simplifications/limitations and uncertainties
Vehicle end-of-life	• As also indicated above, the specific impacts of certain recycled/secondary materials were not available in the background LCI database (Ecoinvent) and had to be approximated based on the relative differentials vs virgin/primary materials for other similar materials. • Future potential recycling rates and material recycled content are uncertain for new materials such as CarbonFRP. • Improved battery recycling techniques (e.g. battery dismantling and pre-treatment, hydrometallurgical recycling processes) are still under development, and so there is inherent uncertainty within the assumptions used in our analysis (based mainly on the GREET model).

6 Conclusions and recommendations

This final chapter presents a discussion and summary of the key conclusions and recommendations drawn from the analysis completed in this study.

6.1 Key findings and recommendations

Based on a review of literature and extensive consultation with expert stakeholders, the project team have developed and applied an LCA methodology to provide a detailed set of results and conclusions. A high-level summary of the work and the main conclusions and recommendations is provided in the following subsections below, with a more detailed summary and discussion also provided in Section 6.2 (on findings and conclusions) and Section 6.3 (on recommendations).

6.1.1 Summary of the scope and main outputs

The scope for this study is highly comprehensive; Figure 6.1 below provides an illustration of the scope of this vehicle LCA compared with the most detailed reference studies and vehicle LCA models found in the literature review. In summary the scope of the study has:

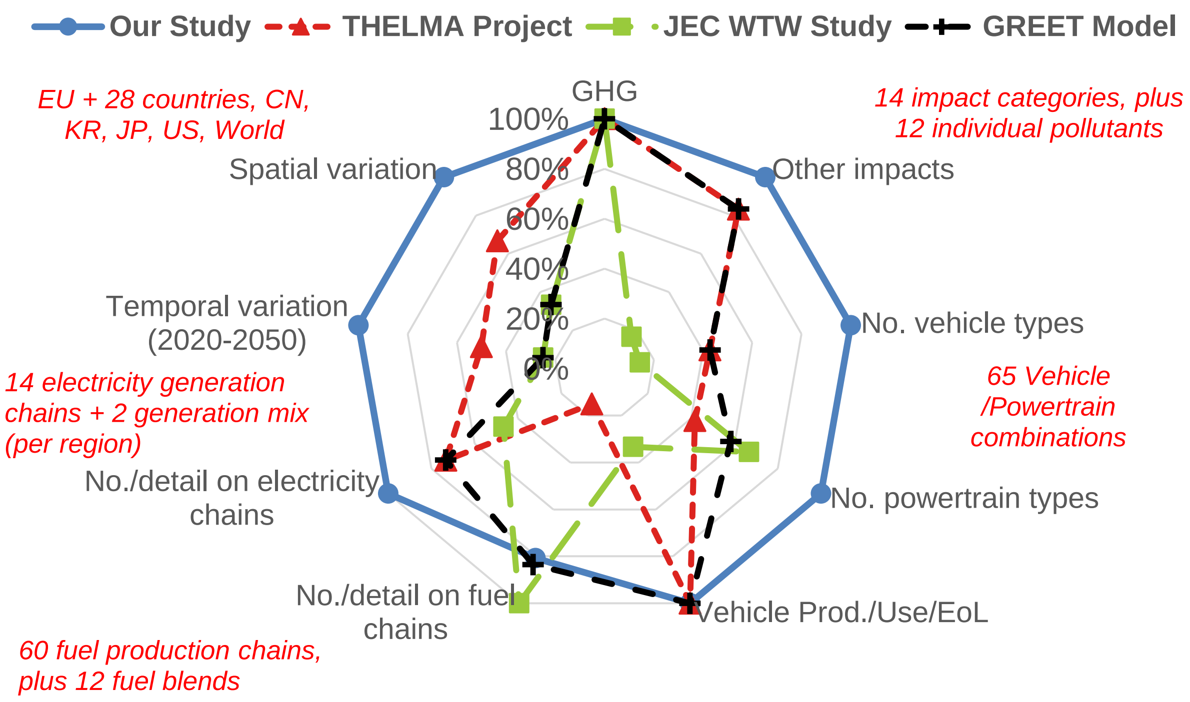
- Explored two **high-level scenarios** based on analysis supporting the Commission's Long-Term Strategy (i.e. Baseline and a lower carbon future - Tech1.5 scenario).
- Explored 14 different **electricity production chains**, covering the EU28 and its individual Member States (relevant for vehicle manufacturing, and electric vehicle operation), and five other world regions (China, S. Korea, Japan, the US and the global average) (for manufacturing only).
- Explored 60 different **liquid and gaseous fuel production chains**, covering 5 fuel categories, 21 feedstocks, and over 20 processes, plus two fuel mix/blend scenarios for each fuel category.
- Explored 65 different generic **vehicle type/powertrain combinations**, across seven light- and heavy-duty vehicle body types.
- Explored 14 different **sensitivities** exploring the significance and impacts of key assumptions and uncertainties for the comparative analysis of different vehicles/powertrain and fuel types.
- Developed a harmonised and consistent comparison of the environmental performance of seven different vehicle types for all stages of the vehicle life-cycle when using specific modelling parameters for fuel chains.
- Undertaken novel methodological development in key areas, to allow future changes in the impacts of key materials and energy chains to be accounted for in a systematic way across the whole vehicle and fuel/electricity system, also including the treatment of vehicle mileage and end-of-life treatment.

In conclusion, the main outputs of the study:

- Provide robust and internally consistent[30] indications on the relative performance of different options, particularly for vehicle powertrain comparisons, electricity chains and conventional fuels.
- Provide a clear indication on the relative environmental impacts of different life-cycle stages.
- Provide good evidence on the temporal and spatial considerations influence lifecycle performance and how potential future developments (in technology or electricity supply) are likely to affect these powertrain comparisons.

[30] In the context of this study, internally consistent means that robust comparisons were only obtained when conducted between vehicle/fuel chains modelled consistently, e.g. using the same LCA scope (attributional or consequential) or co-product allocation approach (e.g. energy allocation), and a fully consistent approach/methodology and dataset for all vehicle types and powertrains.

Figure 6.1: Illustration of the comprehensive scope of this vehicle LCA study compared with other detailed studies and models identified the literature review



Sources: The THELMA project: (PSI/EMPA/ETHZ, 2016), JEC Well-To-Wheels study: (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b); the Argonne National Laboratory's GREET lifecycle model: (ANL, 2018).

6.1.2 Results

The application of the LCA methodology developed in this study has provided an extensive results dataset, using the most current information available at the time of the development of the analysis, and are provided alongside this report. The results from the overall vehicle LCA analysis in this project (Section 5.4 of this report):

- Largely confirm / reinforce the findings from other LCA in the literature in terms of the identification of the main impacts and hotspots, and their significance for different stages of the vehicle lifecycle.
- Demonstrate that the hotspots are similar between different powertrain types, though more significant for certain types or applications.
- Prove the overall significant potential benefits of xEVs (and particularly BEVs) already today (based on the current average EU grid mix, and projected improvements in this) across most of the impact metrics assessed in the study, for both light- and heavy-duty vehicle types.
- Confirm a range of key factors that significantly affect the GHG emissions and other environmental impacts over the life cycle of different vehicles through the application of the LCA and detailed and comprehensive set of sensitivity analyses.
- Substantiate that a number of other factors are significantly less important to the overall result than has been suggested by some previous reports.
- Demonstrate that methodological treatments can significantly influence the overall comparisons (e.g. end-of-life stage methodologies for EVs; allocation of LCA impacts over co-products or the inclusion of counterfactual impacts for fuel production chains).

The results for the electricity production chains (Section 5.2 of this report) have shown a clear picture across all the impact categories which were investigated:

- Renewable electricity production results in significantly lower impacts, compared to fossil fuel based generation except in the impact categories Land Use and Abiotic Resource Depletion (in most cases due to the footprint of and materials used in generation equipment).
- Generally, the lowest impacts from electricity generation are seen with a renewable power generation mix with emphasis on wind power, hydro power, solar PV (photovoltaics) and – to a lesser extent – biomass.
- Nuclear energy results in relatively low environmental impacts in most impact categories, on a par with renewables, with the exception of ionising radiation.

For the liquid and gaseous fuel production cycle, results were presented for a number alternative methodological choices, including: (a) allocation by energy OR substitution in multi-functional processes with co-products (b) inclusion OR exclusion of a counterfactual for secondary/waste feedstocks (i.e. a consequential approach), and (c) inclusion OR exclusion of land-use change emissions (primary biogenic fuels).

The results for fuel production chains (Section 5.3 of this report) are more complex:

- When using mainstream LCA modelling choices (energy allocation, no counterfactual), are characterised by a good degree of “internal consistency”, i.e. they generally allow for like-for-like comparison of different vehicles within the boundaries, the data sources, and the data processing (methodological) choices valid for the purpose of this study.
- The implementation of LCA modelling choices (e.g. substitution approach for co-products, use of counterfactual impacts for secondary feedstocks, inclusion of direct and indirect land-use change emissions), provide meaningful conclusions and help identifying relevant future research areas. Limitations nevertheless exist with regards to the robustness of results obtained for several fuel chains when implementing those methodological choices.
- Values for environmental impacts of fuel chains must therefore be taken with caution, with significant uncertainty ranges, due to methodological choices and limitations in the availability and robustness of data.The impacts of these methodological options are explored in the study through sensitivity analyses, and results for *fuel chains were not included in the overall vehicle LCA analysis where data or methodological choices were judged insufficiently robust*.
- For the majority of fuel chains, results obtained for GWP impacts, using either a substitution approach to multi-functionality or an energy allocation approach, were similar. However, for syngasoline and syndiesel which are co-produced in an FT process, the results between the two methodologies can vary by more than 100%.
- When considering the impact of diverting secondary feedstocks (wastes and residues) from an existing use in another sector (e.g. municipal waste incineration for power production), the results illustrate that for the scenarios considered, “counterfactual” environmental impacts could be several times larger than those from fuel processing but could also be large and negative (e.g. avoided emissions from manure storage).
- The electricity sources (e.g. EU average grid vs 100% renewable) used to produce e-fuels significantly affect LCA impact scores.

6.1.3 Methodology

The methodology and background data were harmonised to a great extent for all stages of the life-cycle leading to internal consistency within the system boundaries used for the analysis and a good comparability of the main vehicle LCA results. LCA methodological choices made for this study were:

- Based on the literature review and stakeholder consultation process.
- Generally in accordance with the norms set out for performing a LCA in (ISO14040, 2006) and (ISO14044, 2006), and the general principles of other important guidelines (PEF, ILCD).
- Guided by the goal and scope defined for the LCA but were tempered by the practical feasibility of applying the methodological choice and also the very broad scope of this study.
- Predominantly favoured through the stakeholder consultation process and in many issues, there was almost a consensus on the choice.

A wide range of sensitivities were explored to help understand the importance of key input data and assumptions and uncertainties in operational aspects on the overall results (Section 5.5 of this report).

These sensitivities confirmed the importance of key parameters, such as the electricity mix, but equally showed that the majority of the sensitivities performed did not significantly affect the overall conclusions on the benefits of electric (and other alternative) powertrains compared to conventional gasoline and diesel vehicles.

In terms of highlights in the application of the LCA from a methodological perspective, the project has implemented the PEF Circular Footprint (PEF CF) approach to account for various important aspects relating to end-of-life (EoL) impacts (including aspects relating to allocation and material quality). In addition, the project has uniquely captured a range of different time-dependent aspects in the calculations in a highly systematic way.

6.1.4 Limitations and uncertainties

It is not valid to compare the results from this study with those of other studies characterised by their own analytical boundaries, different data sources, and specific data processing choices. As a result, and in common with most LCA studies, this study cannot be considered to provide definitive, absolute results on the environmental impacts of different vehicles.

The project results have also been developed under specific decarbonisation scenarios, which reflect expected decarbonisation policies and trends. It is worth highlighting that the observed trends in the results at the vehicle level *can only be obtained if* the decarbonisation targets in the power and manufacturing sector are also achieved.

Implementing certain methodological choices (e.g. substitution, counterfactuals) led to some variability in the robustness of data across different fuel chains. This means, mean that **it was not possible to obtain robust results across all fuel chains and this also prevents a direct comparison of fuel chains evaluated through different methodological approaches.**

The WTT results for fuel chains should primarily be used to understand the impact of certain LCA methodological and data choices, rather than to make any definitive judgement about the relative environmental impacts of the different fuel chains evaluated.

Key limitations of the substitution approach to multi-functionality used in this study are that the modelling assumes only one product is displaced by a given co-product and for some fuel chains there is substantial uncertainty over the nature of the displaced product and the GHG emissions associated with displacing it.

6.1.5 Summary

In summary, developing a comprehensive vehicle policy LCA is a highly complex and time-consuming process, requiring a vast amount of data, the necessary utilisation of a range of key assumptions and standard datasets which can have a profound impact on the results, and a range of methodological decisions – some of which do not currently have good agreement across all major stakeholder groups.

Overall the study shows (with a wide range of sensitivities) the consequences of methodological choices and key assumptions used in the LCA on the resulting environmental impacts of vehicle and energy chains and how potential future developments may affect these comparisons.

6.1.6 Recommendations for future work

Some of the uncertainties and limitations found within the study could be explored in any future work. These include further work or enhancements to build on this study in the following areas:

- Background LCI dataset.
- Vehicle specification.
- Battery manufacturing.
- Vehicle operation.
- Vehicle/battery end-of-life.
- Electricity production chains.
- Fuel production chains.

The following areas were out of scope of the LCA boundary used in this study, but could be beneficial to further explore in future work:

- Refuelling, recharging and ERS infrastructure.
- Road infrastructure.

- Whole-system/fleet life-cycle impacts.
- Effects of new technologies (e.g. C-ITS and autonomous vehicles) on production/disposal, infrastructure and operational efficiency.

Finally, Appendix A6 of this report provides a high-level discussion of the potential changes necessary for application of the developed methodology for possible EU reporting on life cycle CO_2 emissions.

6.2 Detailed findings and conclusions from the analysis

6.2.1 Conclusions for the overall LCA findings

The study has explored a wide range of environmental impacts for 65 combinations of generic light- and heavy-duty road vehicle and powertrain types, as well as the sensitivity of those impacts to variations in fuel chains, fuel blends and electricity mixes.

Overall, this study has been successful in developing a harmonised and consistent comparison of the environmental performance of seven different vehicle types for all stages of the vehicle life-cycle when using specific modelling parameters for fuel chains (see default in Section 5.5.8). These results provide a broad and deep dataset allowing for the further investigation of individual impacts, as well as for comparing across different impact categories. Importantly, passenger cars have previously attracted significantly greater attention than other vehicle types in the papers and reports, and study has expanded the analysis to systematically cover most vehicle categories. The study has also undertaken novel methodological development in key areas, in particular to allow future changes in the impacts of key materials and energy chains to be accounted for in a systematic way across the whole vehicle and fuel/electricity system, also including the treatment of vehicle mileage and end-of-life treatment. However, limitations exist with regards to the robustness of (WTT) results obtained for several fuel chains (discussed further in later Section 6.2.4).

These novel developments, and the ability to adjust key input data used in the calculations in the modelling, have also allowed the consequences of the methodological choices and key assumptions used in the LCA on the calculated environmental impacts to be examined, and for the identification of potential impact hotspots, areas of uncertainty and areas for potential future improvement.

As a result, the main outputs from this study overall *do* provide robust and internally consistent indications on the relative performance of different options, particularly for vehicle powertrain comparisons, electricity chains and conventional fuels. Furthermore, it provides a clear indication on the relative environmental impacts of different life-cycle stages, good evidence on how temporal and spatial considerations influence lifecycle performance and how potential future developments (in technology or electricity supply) are likely to affect these powertrain comparisons.

6.2.2 Results

The application of the LCA methodology developed in this study has provided an extensive results dataset, using the most current information available at the time of the development of the analysis, and are provided alongside this report. The conclusions drawn from the project results (Section 5.4 of this report) are summarised under four areas: environment hotspots; electricity production cycle; liquid and gaseous fuel production cycle and; key influencing factors.

6.2.2.1 Environmental hotspots

The results from the analysis in this project largely confirm / reinforce the findings from other LCA in the literature in terms of the identification of the main impacts and hotspots, and their significance for different stages of the vehicle lifecycle. This analysis has demonstrated that the hotspots are similar between different powertrain types, though more significant for certain types or applications. For example, the general findings from the analysis shows that:

- Impacts resulting from vehicle energy consumption (i.e. mainly TTW impacts, and to a smaller degree WTT impacts) dominate the overall lifecycle impacts for conventional ICEVs (and HEVs) across all vehicle categories, currently accounting for over 82% of GHG impacts for passenger cars and vans, and significantly higher for higher mileage heavy-duty vehicles.

- In other impact categories a larger proportion of impacts are from the manufacturing stage (e.g. AcidP, POCP, PMF), and in some cases the manufacturing stage is always the largest (e.g. EutroP, HTP, ETP_FA, ARD_MM)[31].
- For CED, ODP and WaterS, the WTT (fuel or electricity production) stage dominates overall impacts and for the remaining impact categories (i.e. IRP, LandU)[32] the dominant stage varies the WTT stage if it is an xEV powertrain, or manufacturing, if not.
- The main impacts from vehicle manufacturing are a result of the materials used in the vehicle, and certain materials are more significant for the overall footprint for certain impact categories (e.g. copper for resource depletion and human toxicity). The exception is for battery manufacturing, where impacts from energy consumption are a significant component.

Identification of simple/specific targets or actions to reduce impacts across multiple categories can in some cases be difficult as a result of the highest shares of impacts falling in different stages. However, this study has shown that LCA can be a useful tool to help do this, and could potentially help in tracking and demonstrating progress in reducing key impacts from the vehicle lifecycle in the future.

For alternative powertrains the key findings from the analysis show that:

- Currently, energy consumption (WTT and TTW) impacts also play a key role for other powertrain types such as xEVs, though the WTT elements dominate; however, the significance of these impacts are expected to decrease (significantly) in the future with shifts to higher proportions of low carbon electricity generation, and further deployment of lower carbon fuels.
- The results for plug-in EVs (i.e. PHEV, REEV and BEV) are highly dependent on the electricity generation mix (which varies significantly across the EU).

The overall results from the LCA calculations have, nevertheless, proven the overall significant potential benefits of xEVs already today (based on the current average EU grid mix, and projected improvements in this) across most of the impact metrics assessed in the study. In particular, under the default EU-average assumptions, BEVs have (significantly) lower lifecycle impacts than all of the powertrains assessed for GHG emissions and for many other impacts for <u>all types of vehicles</u> (i.e. both light- and heavy-duty vehicles) analysed, and also across all of the time periods analysed. For light-duty vehicles, the benefits of BEVs are greatest for Large SUVs (that have the highest average lifetime mileages), and heavy-duty vehicles the benefits of BEVs were greatest for buses (due to their urban duty cycle).

The analysis has, however, also highlighted key dependencies and environmental impact hotspots for xEVs when compared to conventionally fuelled vehicles, which principally fall into the following areas:

- *Certain (non-GHG) impacts are higher for plug-in xEVs (i.e. PHEV, REEV, BEV) due to electricity consumption*: these vary by impact mid-point and generation type (discussed in Section 6.2.2.2). However, impacts from biomass generation appear to be the main contributor in a number of cases (notably for the land use category), whilst impacts from nuclear power generation are naturally the main contributor to their higher impacts for ionizing radiation potential (IRP) metric.
- *There higher impacts for xEVs in the areas of human- and freshwater eco- toxicity potential (HTP, ETP) and for Abiotic Resource Depletion (ARD) of minerals and metals:* these are due to key materials used in vehicles, in particular copper, electronic components (also likely to be more significant in premium vehicle models) and also certain other battery materials.
- *FCEVs impacts are higher versus other xEVs for cumulative energy demand (CED) and for water scarcity:* These impacts are particularly significant for hydrogen production by electrolysis of water, and have implications for the efficient use of limited renewable energy versus direct use in BEVs.
- *There are potential impact hotspots relating to platinum group metals:* in certain impact categories (notably particulate formation potential) the impacts for particularly gaseous fuelled vehicles are higher than other types due to the use of platinum in aftertreatment catalysts and fuel cells.

However, based on the assumed shift to lower carbon electricity (for manufacturing and vehicle operation), and technical improvements to batteries, most of these currently higher impacts for xEVs are calculated to significantly reduce in future years. The results therefore appear to confirm the current

[31] GWP = Global Warming Potential, AcidP = Acidifying Potential, EutroP = Eutrophication Potential, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ETP_FA = Freshwater Aquatic Eco-Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity.
[32] CED = Cumulative Energy Demand, IRP = Ionizing Radiation Potential, ODP = Ozone Depletion Potential, LandU = Land Use.

over-arching strategy for increasing electrification of road transport is sound to address GHG emissions, as well as providing benefits in a wide range of other areas.

6.2.2.2 Electricity production cycle

As outlined in Section 5.2 the overall impact of both current and future electricity generation (used as a proxy to electricity available to transport end users) is highly dependent on the composition of the electricity production system. This holds true for all products (e.g. electricity based synthetic fuels or components of a vehicle) or product systems (e.g. electro mobility in general) where electricity is a significant input to a lifecycle stage.

The results for the electricity production chains have shown a clear picture across all the impact categories which were investigated. Renewable electricity production results in significantly lower impacts, compared to fossil fuel based generation (see Section 5.2 for reference) except in the impact categories Land Use and Abiotic Resource Depletion. Generally, the lowest impacts from electricity generation are seen with a renewable power generation mix with emphasis on wind power, hydro power, solar PV (photovoltaics) and – to a lesser extent – biomass.

Nuclear energy results in relatively low impacts in most impact categories, on a par with renewables, with the exception of ionising radiation. Against the background of not taking into account potential accidents and the yet to be solved question how to handle nuclear wastes in the long term, nuclear electricity production performs favourably when compared with a fossil fuel based power generation, especially in the impact category Climate Change.

6.2.2.3 Liquid and gaseous fuel production cycle

The study explored a wide range of environmental impacts for 60 fossil and alternative road transport fuel chains. Results were presented for a number alternative methodological choices, including: (a) allocation by energy OR substitution in multi-functional processes with co-products (b) inclusion OR exclusion of a counterfactual for secondary/waste feedstocks (i.e. a consequential approach), and (c) inclusion OR exclusion of land-use change emissions.

Since the handling of liquid and gaseous fuel production chains was (by necessity) more complex, varied and extensive than for electricity chains, a more comprehensive discussion of the conclusions that can be drawn from the work in this area. There are also a number of important limitations and uncertainties for the analysis, which are discussed separately in later Section 6.2.4.

Implementing certain methodological choices (e.g. substitution, counterfactuals) led to some variability in the robustness of data across different fuel chains. This means that **it was not possible to obtain robust results across all fuel chains and this also prevents a direct comparison of fuel chains evaluated through different methodological approaches.** For example, it is not possible to compare the results obtained for primary fossil fuels with those for biogenic fuels when a substitution methodology is applied, as results are only available on an energy allocation basis for fossil fuels. Results for fuel chains being evaluated through consequential LCA, which require a counterfactual scenario for use of the feedstock to be developed, should also be considered with caution, as the breadth of the study did not allow for a comprehensive analysis of counterfactual scenarios. The alternative fuel chain results presented using an energy allocation across all fuel chains modelled and no counterfactuals are more readily compared directly, and have been used as the default in the main overall vehicle LCA (discussed in Section 6.2.1).

Therefore, the WTT results for fuel chains presented in this report should primarily be used to understand the impact of certain LCA methodological and data choices, rather than to make any definitive judgement about the relative environmental impacts of the different fuel chains evaluated. In order to allow for better comparability of fuel chains, the Vehicle LCA Results Viewer allows the results from alternative calculation methodologies to be compared where these are consistently applied across all chains (e.g. energy allocation for all chains or removal of counterfactuals in secondary chains).

A comparison of results from this study for crude-derived fuels with those calculated by the JEC using the CONCAWE model illustrated that on a well-to-tank basis, the GWP for gasoline and diesel calculated by the JEC using was 8% higher for diesel and 5% lower for gasoline. Results for non-GWP impacts are comparable across all crude-derived fuels, although fuels derived from non-conventional crude result in higher lifecycle PM and SO_x emissions and a higher water scarcity score than fuels derived from conventional crude oil.

The effect on the calculated GWP impacts of implementing a substitution approach to multi-functionality rather than an energy allocation approach was investigated. For the majority of fuel chains, results obtained using the two different approaches were similar. However, for syngasoline and syndiesel which are co-produced in an FT process, the results between the two methodologies can vary by more than 100%, as detailed in Section 5.3.2.2. Given the similarities between the FT and refinery production system, with multiple energy products from each unit of feedstock, it is particularly important that if the impacts of synthetic fuels are to be compared with those of fossil fuels, the same approach to multi-functionality is used.

Secondary feedstocks (wastes and residues) are expected to provide an increasing share of transport fuels and are strongly incentivised in RED II, e.g. through a specific sub-target and double counting. They are considered under the RED methodology to have zero GWP until the first point of collection. In this study, the impact of diverting secondary feedstocks from an existing use in another sector (e.g. municipal waste incineration for power production) was included. The results illustrate that for the scenarios considered, counterfactual environmental impacts could be several times larger than those from fuel processing but could also be large and negative (e.g. avoided emissions from manure storage).

While the magnitude of indirect land-use change remains a controversial issue, the importance of considering it alongside direct land-use change was acknowledged as a necessity by a majority of stakeholders. The Land-Use Change (LUC) values used in this study were close to those included in the iLUC Directive/RED II, except in the case of palm oil. This is because only one unique value for vegetable oil is currently used in RED II, but additional disaggregation shows palm oil had a substantially higher LUC value. As expected, adding LUC emissions from GLOBIOM (including iLUC), which assume a 20-year amortisation period, takes primary biogenic fuels to a level of impact close to fossil fuels. The use of longer amortisation periods for LUC emissions could not be experimented within the scope of the study, which would have a significant impact on results.

Finally, the electricity sources (e.g. EU average grid vs. 100% renewable) used to produce e-fuels significantly affect LCA impact scores, as illustrated in Section 5.3.2.5.

6.2.2.4 Key influencing factors

The application of the LCA, and the detailed and comprehensive set of sensitivity analyses included, have confirmed a range of key factors that significantly affect the GHG emissions and other environmental impacts over the life cycle of different vehicles. It has also demonstrated that a number of other factors are significantly less important to the overall result than has been suggested by some previous reports. The following Table 6.1 provides a qualitative summary of the findings, showing the relative importance/influence of a number of factors on the overall (GHG) impacts for ICEV/HEV and for xEV powertrains, and their overall influence on the result *for the comparison between the two.* This summary is based mainly on a combination of the main results (in Section 5.4) and the various sensitivities performed on key assumptions/settings (presented in Section 5.5), as well as the additional information provided in Appendix A5.

The Table 6.1 illustrates that whilst factors relating to vehicle operation generally have the highest effect on the overall impacts, they do not always on average have a similarly high effect on the comparison between powertrains. For example, accounting for potentially lower freight capacity/loading by varying the average loading fractor for lorries has a High (H) percentage impact on the overall emissions per tonne-km for *both* ICEV/HEV powertrains, as well as for xEV powertrains once the combined effects of tonnes loading and impacts on energy consumption per km are factored in. However, this resulting combination does not significantly affect the relative comparison of these powertrains, so the net effect is Low (L).

The most significant factors for the comparison in Table 6.1 are generally those where there is a marked difference between their influence on ICEV/HEV or xEV powertrains. However, in some cases this can even out – for example, although the energy consumption (/electric range) of plug-in electric vehicles is significantly affected by very cold weather (and to a lesser extent higher temperature conditions), this does not markedly affect the relative comparison of impacts vs ICEVs. This is because the larger effect (M/L in the table) in percentage terms on the WTW impacts for xEVs is balanced out compared to a smaller percentage impact (L, in the table) for ICEVs on a significantly higher WTW impact.

Table 6.1: Qualitative summary of the relative importance of key factors influencing the total lifecycle GHG impacts of road vehicles for different powertrain types

	Element	ICEVs and HEVs		xEVs		Comparison of ICEV/HEV and xEV	
		Current	Future	Current	Future	Current	Future
O	Operational energy consumption (and direct vehicle air pollutant emissions)	H	H/M	L	VL	H	H
O	Lifetime activity (in km) and the age-dependent annual mileage profile	H	M	M	L	M	M/L
O	Duty cycle, driving patterns / share of driving on different road types (regional)	M	M	M	M	M	M
O	Average freight loading factor and the degree to which the vehicle is being used on a weight-limited operation	H	H	H	H	L	L
O	Ambient temperature effects on energy consumption (regional)	L	L	M/L*	L	M/L	L
O	Electricity production mix for charging of xEVs (regional)	*N/A*	*N/A*	H	M	H	M
O	Fuel blends and methodologies	H	H/M	(M/L**)	(M/L**)	H	M
O/S	PHEV charging behaviour and electric range combination	*N/A*	*N/A*	H	M	H	M
S	The electric (or gaseous fuel) range	*N/A*	*N/A*	L	L	L	L
S	Battery specification and characteristics	*N/A* (L****)	*N/A* (L****)	L***	L***	L	VL
S	Vehicle glider material composition	M	L	M	L	L	L
ME	Improvements in vehicle manufacturing and the use of renewable energy	L	L	L	L	L	L
ME	Improvements in battery manufacturing and the use of renewable energy	*N/A*	*N/A*	M	M/L	M	M/L
ME	End-of-Life treatment and recycling	L	L	M	L***	M	L***
ME	Variation in battery end-of-life recycling, and potential for 2nd life applications	*N/A*	*N/A*	M/L***	L***	M	L***

Notes: * mitigated or xEVs with heat pumps. ** PHEVs and FCEVs only; *** much more significant effect for resource depletion and human toxicity impacts. **** for HEVs only.

Key for impacts: H = High, M = Medium, L = Low, VL = Very Low.

Lifecycle stage: O = vehicle operation, S = vehicle specification, ME = vehicle manufacturing and end-of-life.

A further consideration is that methodological treatments can also significantly influence the overall comparisons, as well as the mentioned key factors (and corresponding assumptions); this is particularly the case for the end-of-life stage methodologies, and especially for electric vehicles.

In the real-world, a combination of these factors may add up in certain specific situations/use cases to significantly influence the relative performance of different powertrain and fuel combinations (e.g. electric vehicle with a bigger battery, driving with relatively low mileage/short journeys in a country with higher electricity impacts – or charging during peak demand periods – versus HEV operating in a country with a relatively high share of sustainable biofuel). Therefore it is important to match a particular vehicle/fuel and configuration/specification to a particular intended application to maximise benefits (e.g. in the above example the comparison could be improved with a low-range EV charging only overnight/in low periods of demand where abundant lower carbon electricity is available).

A summary discussion of the wider key limitations and uncertainties for the analysis is also provided in Section 6.2.4. Nevertheless, as indicated, there are a number of clear trends that emerge from the analysis that enable robust general conclusions to be drawn on the average relative performance (for a range of impacts) of the different vehicle types and powertrain/fuel options assessed.

6.2.3 Methodology

This study aimed to develop and apply an overall vehicle LCA methodology intended to inform the further development of climate change, energy, air quality, and transport related policies for the mid- to long-term timeframe (2020 to 2050).

Despite the ambitious scope of the study, the methodology and background data were harmonised to a great extent for all stages of the life-cycle leading to internal consistency within the system boundaries used for the analysis and a good comparability of the main vehicle LCA results. However, some limitations exist for the comparability between certain fuel chains results where there are differences in the LCA methodological choices, datasets and assumptions used across fuel categories (see Sections 5.3 of the results, and Section 6.2.2.3 below), thus leading to specific adaptations of the WTT modelling parameters to improve comparability and robustness of the vehicle LCA.

The LCA methodological choices made for this study (e.g. for system boundaries, attributional versus consequential, allocation methods, use of counterfactuals, end-of-life treatment, background/foreground data, etc.) were based on the literature review and stakeholder consultation process. These choices are also generally in accordance with the norms set out for performing a LCA in (ISO14040, 2006) and (ISO14044, 2006), and the general principles of other important guidelines (PEF, ILCD). The choices made were guided by the goal and scope defined for the LCA, but were tempered by the practical feasibility of applying the methodological choice and also the very broad scope of this study. The stakeholder consultation predominantly favoured the chosen methodological approaches, and in many issues there was almost a consensus on the choice.

The objective of the implementation of the developed methodology has been to assess the impact of LCA methodological choices on the relative performance of vehicle/powertrain combinations over different impact categories and how this might evolve in the period to 2050. In addition, the study has aimed to identify potential hotspots and the key factors influencing these impacts. With that in mind, a wide range of sensitivities were also explored to help understand the importance of key input data and assumptions and uncertainties in operational aspects on the overall results. These sensitivities confirmed the importance of certain parameters, such as the electricity mix, but also equally showed that the majority of the sensitivities performed did not significantly affect the overall conclusions on the benefits of electric (and other alternative) powertrains compared to conventional gasoline and diesel vehicles. The foreground input data and sensitivities for the overall vehicle analysis were also informed by the literature review, various stakeholder consultation activities, previous work by all partners and by Ricardo's engineering expertise on road vehicles, powertrain technologies and battery systems.

In terms of highlights in the application of the LCA from a methodological perspective, the project has has implemented the PEF Circular Footprint (PEF CF) approach to account for various important aspects relating to end-of-life (EoL) impacts (including aspects relating to allocation and material quality). In addition, the project has uniquely captured a range of different time-dependent aspects in the calculations in a highly systematic way - e.g. that credits from recycling materials and energy recovery at the end of the life of the vehicle will be lower due to reduction in impacts of virgin materials (and the offset energy impacts) compared to those at the time/point of manufacture of the vehicle. However, the LCA EoL methodological approach remains a topic with significant variation in views on the optimal approach, with some stakeholders still preferring a simpler approach that can be more readily understood and communicated also to non-experts.

Nevertheless, some uncertainties and limitations remain for the methodology and data, some of which could usefully be explored in any future work, which are discussed further in later Section 6.3.

6.2.4 Key limitations and uncertainties for the analysis

As discussed above, LCA modelling of vehicles is complex and requires methodological choices, some of which result in important variations in results. In addition, particularly for LCA studies such as this one which have a broad scope, the assumptions which must be made to allow modelling of vehicles or fuel chains are inevitably either context-specific or averaged to cover a range of situations.

The results presented in this report, when using specific modelling choices for fuel chains (energy allocation, no counterfactual), are characterised by a good degree of "internal consistency", i.e. they generally allow for like-for-like comparison of different vehicles within the boundaries, the data sources, and the data processing (methodological) choices valid for the purpose of this study.

However, it is not generally valid to compare the results from this study with those of other studies characterised by their own analytical boundaries, different data sources, and specific data processing choices. As a result of the above caveats, and in common with most LCA studies, this study cannot be considered to provide definitive, absolute results on the environmental impacts of different vehicles.

It should be noted that limitations exist with regards to the robustness of (WTT) results obtained for several fuel chains. In such cases the absolute values must be taken with caution, with significant uncertainty ranges, due to the novel nature of several methodological choices and limitations in the availability and robustness of data. However, the impacts of these alternative methodological options are explored in the study through sensitivity analyses, and results for fuel chains were not included in the overall vehicle LCA analysis where data or methodological choices were judged insufficiently robust.

It is evident from the literature survey that considerably less literature and data is available for certain vehicle types (mainly trucks and buses), powertrains and fuels (especially e-fuels and synthetic fuels). This may lead to higher uncertainties for these vehicles/energy types; future work could focus on improving the robustness of the primary data used to define these.

Whilst the LCA results have helped identify the hotspots mentioned in Section 6.2.2.1 above, it is also important to highlight areas where there are limitations in the current approaches or metrics. A broad range of environmental impacts were considered in this project, and the robustness of data on the flows which contribute to these impacts will vary significantly with some flows being less well characterised, and having a higher degree of uncertainty. Care should therefore be taken in result interpretation; especially for less common impacts where methodologies for calculating impacts are also less well established (see also discussion in chapter 3.1.5.2).

In addition, key battery materials such as cobalt and lithium do not significantly influence the overall impacts for the assessed LCA impact categories (e.g. for resource depletion), due to their low percentages of the total mass of batteries/vehicles. Nevertheless, such materials have previously been identified as critical with respect to current supply and potential future demand and have a resource constrained supply localised in a few key world regions. This may suggest the current mid-point LCA indicators/ single-vehicle approach is not sufficient to identify potential economic issues of this type. In such cases a system-wide analysis is needed to complement LCA, to identify such issues.

For fuels, different methodological approaches, assumptions and data sources are also tested in this study, some of which were novel in nature or utilised data with significant underlying uncertainty. This means that the results should not be taken as an accurate, consistent representation of impacts across *all* of the fuel chains investigated. (An assessment of the robustness of different fuel chains is provided in the report Appendices). In addition, comparisons should not be made between fuel chains when these are evaluated via different methodological approaches or where data robustness is more limited.

Key limitations of the substitution approach to multi-functionality used in this study are that the modelling assumes only one product is displaced by a given co-product and for some fuel chains there is substantial uncertainty over the nature of the displaced product and the GHG emissions associated with displacing it. Nevertheless, using substitution provides valuable insights on system-wide impacts (e.g. electricity production), which could not be properly addressed via an allocation methodology. For example, in wheat ethanol production, DDGS is produced, which can be used as an animal feed. The DDGS can therefore substitute animal feed from other sources (e.g. soy or cereals). As suggested by the ISO 14040 standard, it is therefore important to prioritise the use of substitution whenever possible.

A key limitation of this study was that only one counterfactual scenario could be modelled for each secondary feedstock, assuming that each feedstock does have an existing productive use. If feedstocks are truly waste, and do not have an existing use, then counterfactual environmental impacts would be zero. Nevertheless, the risk of adverse environmental impacts from diverting secondary feedstocks from existing uses may become more severe in the future as feedstock supplies become constrained. If policy continues to strongly support the use of secondary feedstocks (such as those in Annex IXA of the REDII) for fuel production, these risks should be monitored and mitigated through the assessment of counterfactual environmental impacts. To be accurate, such assessment requires substantial work to define a number of realistic counterfactual scenarios and assess the most appropriate scenario(s) for a given feedstock at a particular time, location etc. Therefore future LCA research and policy work should aim to improve the understanding and generate robust data for the modelling of counterfactual scenarios in LCA.

To mitigate for different methodological approaches or where data robustness is more limited, in the overall vehicle LCA analysis, such fuel chains were generally not included in the fuel blends used, and the more novel methodological options (i.e. applying consequential modelling for secondary feedstocks and handling multi-functionality with a substitution approach) were reserved for the sensitivity analyses.

The project results results have also been developed under specific decarbonisation scenarios, which reflect expected decarbonisation policies and trends. It is worth highlighting that the observed trends in the results at the vehicle level can only be obtained if the decarbonisation targets in the power and manufacturing sector are also achieved.

6.2.5 Summary

What has been made clear from the project is that developing a vehicle policy LCA is a highly complex and time-consuming process, requiring a vast amount of data, the necessary utilisation of a range of key assumptions and standard datasets which can have a profound impact on the results, and a range of methodological decisions – some of which do not currently have good agreement across all major stakeholder groups.

Overall the study shows (with a wide range of sensitivities) the consequences of methodological choices and key assumptions used in the LCA on the resulting environmental impacts of vehicle and energy chains and how potential future developments may affect these comparisons.

6.3 Detailed recommendations for further work

Some of the uncertainties and limitations discussed in the previous section could be explored in any future work. Table 6.2 provides a summary of the current status for different aspects of the vehicle LCA work performed for this study in terms of (i) the methodology developed and applied, and (ii) the quality of the datasets used in the analysis. It also contains recommendations for future work that could expand the coverage or improve the robustness of results; these are sub-divided into those that would further enhance or directly build upon the work completed under this project, and those relating to aspects that were not considered or were outside the scope of this study.

Finally, a future piece of work would also be necessary to explore how the methodology and findings from this study might be built upon and adapted for a possible application in reporting on the life cycle CO_2 emissions of all new vehicles as the Commission is requested to do under the LDV and HDV CO_2 Regulations. As mentioned earlier, high-level discussion of the potential changes necessary for such an application is also provided in Appendix A6 of this report.

Table 6.2: Summary of of the current status for different aspects of the work performed for this study and recommendations for future work

Area	Methods	Data	Recommendation
Areas covered by this study			
Background LCI dataset		/	• Review current datasets and assumptions to improve data quality and fill data gaps particularly for carbon fibre reinforced plastic and for secondary and recycled materials • For key materials further consider other potential improvements to material production (e.g. lower impact extraction, improved process efficiencies, alternative processing methods, etc.), material recycling and reduced impacts from secondary materials
Vehicle specification			• Further refine current assumptions based on improved data (e.g. on the real-world energy consumption performance of HDVs, particularly for new/alternative powertrain types, sizing/specification of components)

Area	Methods	Data	Recommendation
			• Expand analysis to include other vehicle types (e.g. powered 2-wheelers, other car, van or lorry segments)
Vehicle / battery manufacturing			• Improve characterisation of battery manufacturing, particularly for newer and advanced battery chemistries. • Gather more information / data on efficiency improvements in recent years and on effects of future improvements
Vehicle operation			• Further enhancement to methodologies to better capture sensitivities due to other effects such as climatic impacts on energy consumption and emissions, particularly for heavy duty vehicles • More detailed examination of the future potential for reductions in regulated operational air quality pollutant emissions (e.g. taking outputs from current EC projects considering potential for post-Euro 6/VI emissions standards) • Further enhancement to the coverage of impacts due to vehicle maintenance, focusing on areas of potential difference between different powertrain/fuel types • Further exploration of specific vehicle parameters and usage in real-world situations that could be beneficial in future work
Vehicle / battery End-of-Life			• Improve the datasets for a range of key recycled materials. • Further research on of end-of-life recycling and battery second life: LCA methodologies and data. • Additional sensitivity analysis on how the end-of-life methodology applied impacts on the results (e.g. cut-off vs hybrid vs PEF Circular Footprint).
Electricity production chains			• Update input data on future electricity mix projections • Further review and enhance underlying datasets • Broaden the scope of the analysis to investigate the potential contributions of electricity storage requirements on the results
Fuel production chains	 / 	 - 	• Develop improved foreground data-sets for non-conventional natural gas production, hydrogen production from natural gas, and fuel production processes which are currently at an early stage of commercialisation such as e-fuel production. • Model additional counterfactual and substitution scenarios to provide LCA practitioners with guidance and default values and identify feedstocks or fuel production chains which may be at high risk of causing indirect impacts through their use in fuel production: ○ Define standard protocols to model substitution scenarios and default values for co-products by integrating multiple substitutions. ○ Define standard protocols to model counterfactual scenarios for feedstocks, including default values for avoided impacts and impacts from replacing avoided use ○ Further explore variation in land-use change evaluation, in particular GWP amortisation times and adjust recommendations in consequence.

Area	Methods	Data	Recommendation
			• Explore the possibility to model all residues as co-products and allocate a share of the impacts of the primary production process to them. • Improve comparability of fuel chains by expanding novel methodological approaches (e.g. substitution of co-products, use of counterfactuals), which requires robust data sets, especially for novel fuels. • Modelling of additional fuel chains, for example to cover new fuel types (e.g. bio-LPG) or variations on existing fuel chains with different feedstocks (e.g. algal-based biofuels) or processing steps • General exploration and improvement to the temporal harmonisation and granularity of data across all areas.
Areas not covered by this study			
Refuelling, recharging, and ERS infrastructure	☹	☹	• Methodologies and datasets need developing to characterise existing and new infrastructure • Fleet-level modelling/assessment may be needed to appropriately allocate impacts on a vehicle-basis
Other infrastructure	☹	☹	• Expansion of boundary to also consider other road infrastructure elements
System/fleet impacts modelling	☹	☹	• Estimation of whole-system/fleet life-cycle impacts using outputs from this study
Effects of new technologies and trends	☹	☹	• Estimation of further operational effects due to new technology or trends: e.g. effects of C-ITS / ITS and autonomous vehicle technologies on (a) production/disposal of new systems added to the vehicle, (b) impacts of infrastructure, (c) impacts on vehicle operational efficiency / emissions

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Appendices

A1 Appendix 1: Additional information from the Literature Review

This Appendix provides a more detailed summary of the literature review completed for the project, and some additional analysis of methods identified in the literature to characterise the vehicle chain and fuel production chains. It is organised as follows:

- Section A1.1 provides a summary of the hotspots for different environmental impacts identified in the literature review for different vehicle, powertrain and fuel types, with:
    - Section A1.1.1 providing an overview of the different environmental impacts from the complete vehicle lifecycle (i.e. equipment and WTW cycles).
    - Section A1.1.2 focusing on the impacts stemming from the production, maintenance and end-of-life (EoL) stages, that is, the equipment lifecycle.
    - Section A1.1.3 covering the impacts from a range of fuel production chains.
    - Section A1.1.4 identifying the key lifecycle environmental impacts of electricity generation.
- Section A1.2 provides a summary of the identified methodological options from the literature that informed the development of the LCA methodology for this study, including:
    - Section A1.2.1 on vehicle specification and operation
    - Section A1.2.2 on vehicle production, maintenance and end-of-life
    - Section A1.2.3 on fuel production chains

A1.1 Identification of lifecycle environmental impact hotspots

This section of the report provides a summary of the hotspots for different environmental impacts identified in the literature review for different vehicle, powertrain and fuel types to identify areas of more significant impacts that could be the focus of future policy initiatives.

This section is split into four subsections, first providing an overview of the complete vehicle lifecycle, and then considering separately the equipment cycle (production, maintenance and disposal), the fuel and the electricity cycles (WTW) only.

A1.1.1 Overview

This section provides an overview of the different environmental impacts from the complete vehicle lifecycle (i.e. equipment and WTW cycles). Based on the literature reviewed, it aims to:

- Investigate how well the different impact categories are covered by the literature as well as uncover the reasons for the more frequent reporting of certain impact categories over others.
- Assess the variability in impact estimates found in the literature.
- Understand key differences by powertrain and vehicle types.
- Explore the relative importance of the different lifecycle stages.
- Identify key assumptions which determine the overall vehicle impacts and consider future implications for the analysis.

A1.1.1.1 How well are the impacts of vehicles covered in the literature?

The literature provides a range of information on the lifecycle impacts from different vehicle, powertrain and fuel types. The most common environmental impact reported on is GHG emissions or Global Warming Potential (GWP), followed by energy consumption, air quality as well as toxicity and resource depletion to a lesser extent. The analysis is primarily undertaken for passenger cars and often only considers more common fuel/energy types (e.g. conventional petrol, diesel fuels, and electricity). For example, extremely few studies examined alternative fuel energy chains in detail, as well as the vehicle production/disposal aspects. Most studies provide detailed information on the breakdown of impacts between different lifecycle stages, but their technical scope can vary, with some studies assessing the impacts of the complete vehicle lifecycle (i.e. equipment and WTW cycles), whilst others focus only on the WTW cycle or on key vehicle components (e.g. batteries).

We found there is significant variability in the results (see following section for more details) but also that their presentation varies widely between studies. Some studies report the inventory results in terms of emissions and substances, whilst others only present the aggregated results into midpoint indicators (there are studies that report both). Other studies go beyond and complement this information with estimates for endpoint indicators based on widely used methodologies such as ReCiPe.

Regarding the choice of environmental impacts reported in the literature, not many LCA studies explicitly provide a justification for the emissions and/or indicators they assess. Among those that do, Box 1 provides some examples of the reasons found in the literature.

Box 1: Selected examples of reasons for choice of environmental impacts covered

(PSI/EMPA/ETHZ, 2016) (Thelma Project) notes that their selection of impact categories for passenger cars (which includes cumulative GHG emissions, PMF, POFC, TAP and ADP) represents the range of environmental concerns and damages to which passenger vehicles are anticipated to contribute most significantly, selected on the basis of expert judgment.

(Ercan & Tatari, 2015) whose analysis focusses on busses indicates that their choice of environmental impacts covered (including GHG, CO, NOx, PM10, SO2 emissions) is based on their widespread reporting in the literature and their relative importance compared to other pollutants.

In the case of an OEM's Environmental Product Declaration, (Renault, 2011) provides a detailed reasoning for their coverage of environmental impacts which is based on three aspects: expected and know contributions of the vehicle; diversity of ecosystems, local biodiversity, global resources depletion; indicators recommended by experts and the European automotive industry. They adapted an evaluation matrix from ADEME, the French Environment and Energy Agency, focusing on four criteria (relevance, feasibility, consistency and reliability) to make their selection (includes GWP, EP, POCP, TAP, ADP but exclude aquatic eco-toxicity, biodiversity, and land use change). In addition, they also decided to include primary energy demand (also referred to as cumulative energy demand) due to its importance for EVs (despite acknowledging it is closely linked to ARD). They also justified why they have not included other indicators such as HTP (due to lack of data and uncertainty of results), carcinogens substances (due to difficulties in evaluating impact on human health), water consumption (due to complex problem, lack of agreed methodology), and non-exhaust emissions (due to lack of data, uncertainties regarding origin and variability linked to components and suppliers).

Overall, the choice of impact categories covered in the literature (either explicitly or implicitly justified) appear to be based on the impacts assessed by previous studies (to allow comparisons) and/or expert judgment on which impacts are most relevant for vehicle lifecycle (i.e. those impacts for which the vehicle is expected to contribute the most).

The level of detail of the analysis is also found to vary significantly. Some studies provide more detailed information and data than others, but overall we find there is less information available and greater uncertainty regarding certain lifecycle stages (e.g. maintenance and end-of-life) and impacts (e.g. toxicity and resource use) as well as lack of detail on the source of impacts (e.g. vehicle components principally responsible for impacts not being identified).

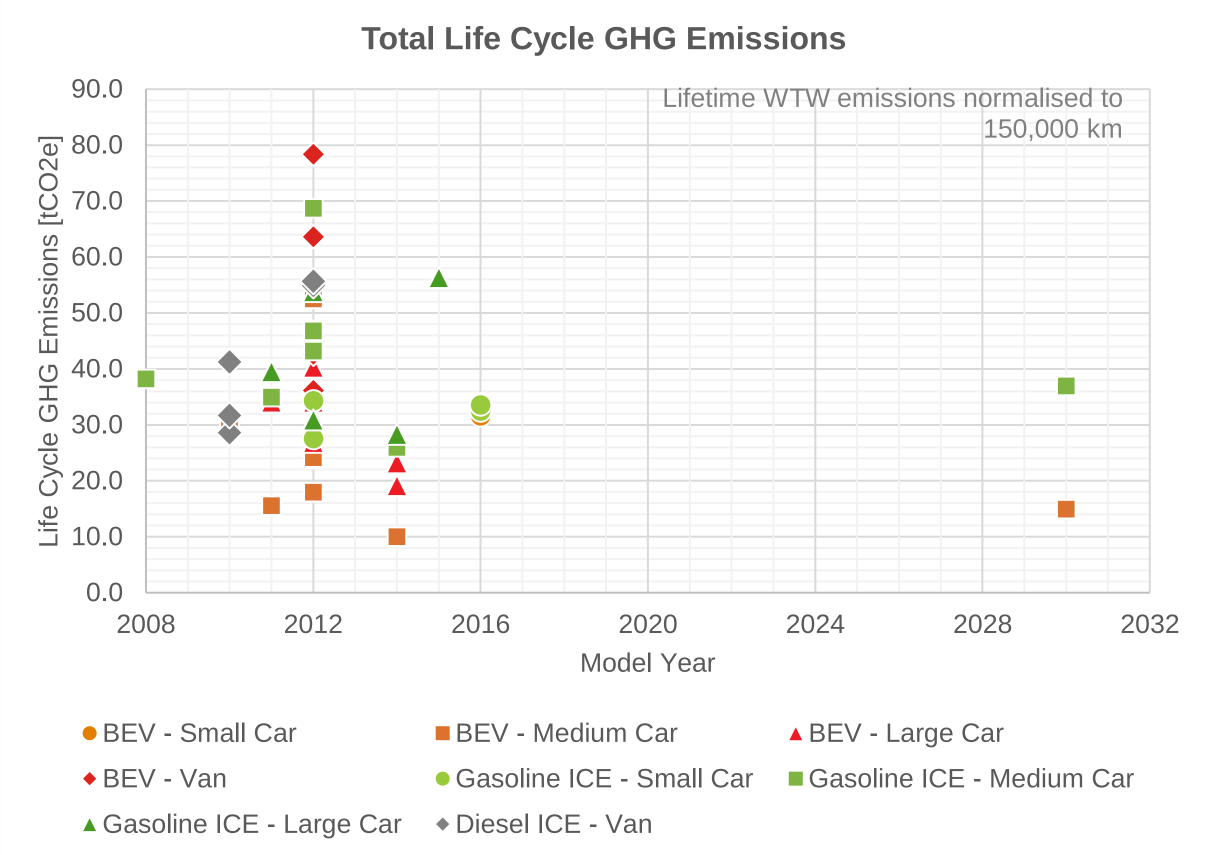
A1.1.1.2 What is the variability in estimates for impacts from the vehicle lifecycle?

We find there is significant variability in estimates of impacts reported by the literature. As an example, Figure A1: illustrates the range of results in terms of lifecycle GHG emissions from BEVs and ICEVs reported in studies published between 2010 and 2016. Even after normalising lifetime mileage (to 150,000 km[33]), the total lifecycle GHG emissions of BEVs vary between 31.6 – 33.8 tonnes for the small car, 10 – 52.5 for the medium car, 19.2 – 46.8 for the large car and 36.1 – 78.4 for the van. Similarly,

[33] 150,000 km is a figure commonly used in LCA of cars and vans, though significantly lower than averages for the EU based on the latest evidence, e.g. (Ricardo Energy & Environment et al, 2016), (TML et al, 2016).

the results for the ICEVs vary widely: 27.6 – 34.4 tonnes of CO_2e emissions for the small petrol car, 26 – 68.7 for the medium petrol car, 28.3 – 56.4 for the large petrol car and 28.6 – 55.6 for the diesel van.

Figure A1: Total lifecycle GHG emissions reported in the literature



Source: Ricardo, compiled from the literature.

Similar differences between studies' estimates are found for the other environmental impact categories – see Sections A1.1.1.3 and A1.1.1.4 below which discuss the results found in the literature.

The observed variability in estimates is mainly the result of differences in data sources and model assumptions, with the most important being:

- Vehicle and powertrain specification.
- Vehicle energy consumption.
- Electricity and fuel carbon intensity.
- Lifetime of battery and chemistry.
- GHG emissions components included.
- Study methodology (e.g. differences in system boundaries, end-of-life treatment, etc).

This highlights the importance of clearly presenting the choice of assumptions and data sources when reporting results from LCAs. It also has implications for understanding the environmental burden of different powertrain, vehicle and fuel types as discussed in the following section.

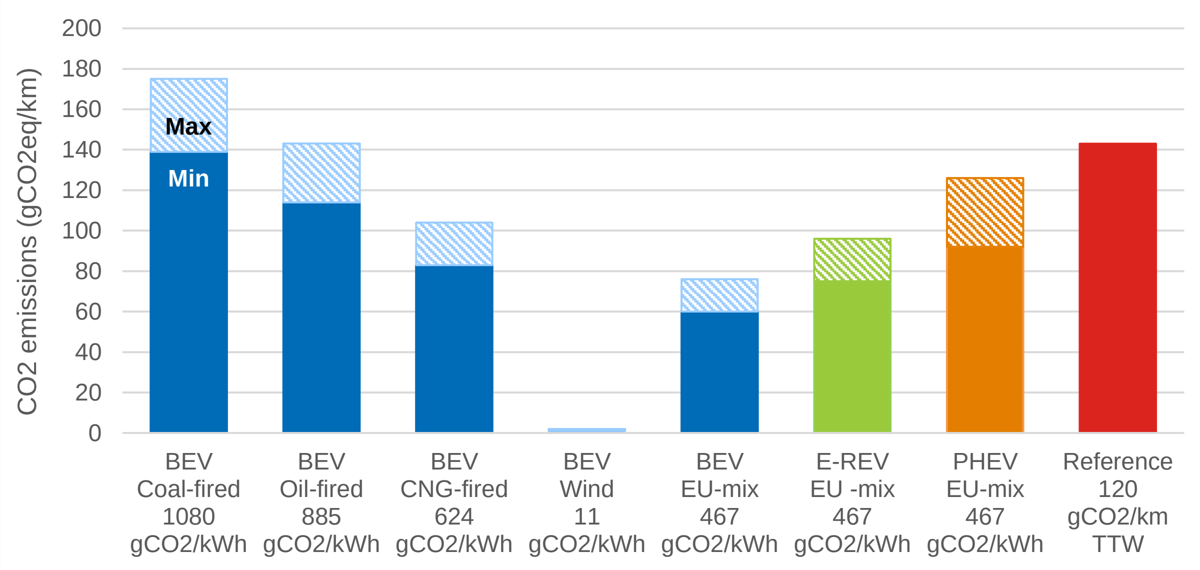
A1.1.1.3 Do impacts significantly differ between powertrains, fuels or vehicle types?

Given their widespread coverage in the literature, we first examine the GHG impacts of passenger cars.

The review of the literature confirms that the GHG impacts from passenger cars vary significantly with powertrain type. Overall, lifecycle GHG emissions from the ICEV tend to be higher than for the equivalent xEV (i.e. PHEV, REEV, BEV or FCEV) as illustrated by Figure A1: above.

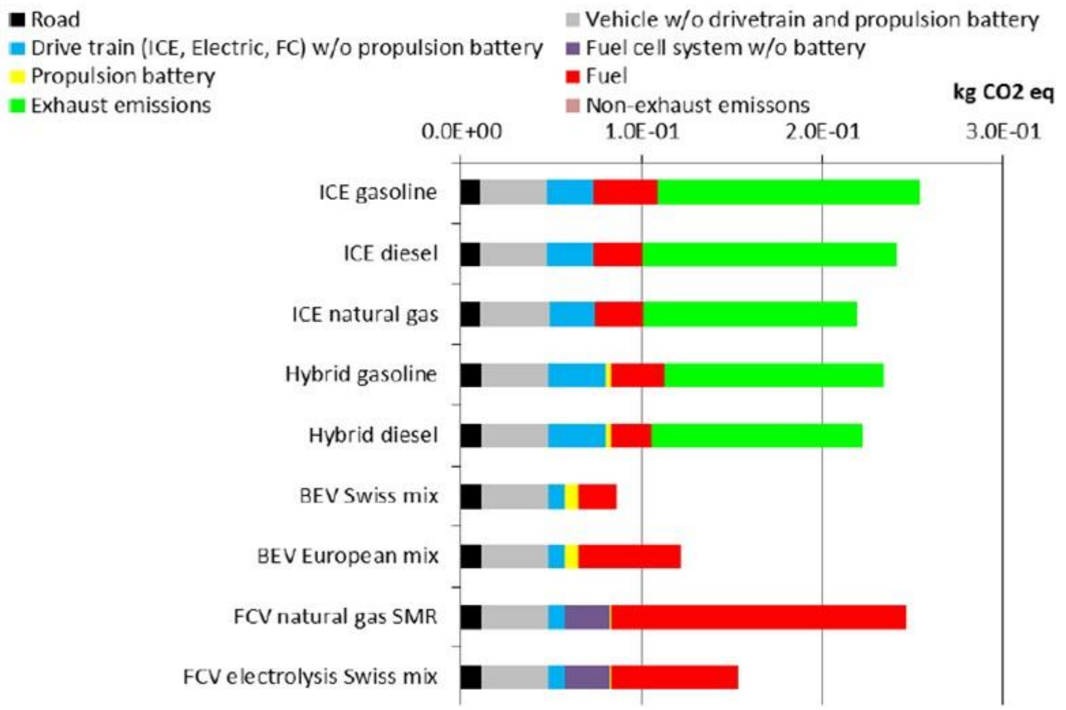
A higher degree of electrification is also found to generate lower GHG emissions in the WTW cycle - Figure A2 - and overall - Figure A3 for the EU average grid mix. As such, the pure electric vehicle usually exhibits a lower environmental burden followed by the hybrid powertrains (PHEV, E-REV, HEV). Although fewer studies have assessed the impact of FCEVs, this powertrain type also appears to achieve reductions in GHG emissions compared to the ICEV as Figure A3 demonstrates.

Figure A2: Impact of degree of electrification and source of electricity production to WTW GHG emissions



Source: Reproduced from (Messagie, 2017)

Figure A3: Life cycle GHG emissions from passenger cars by powertrain type, Thelma Project



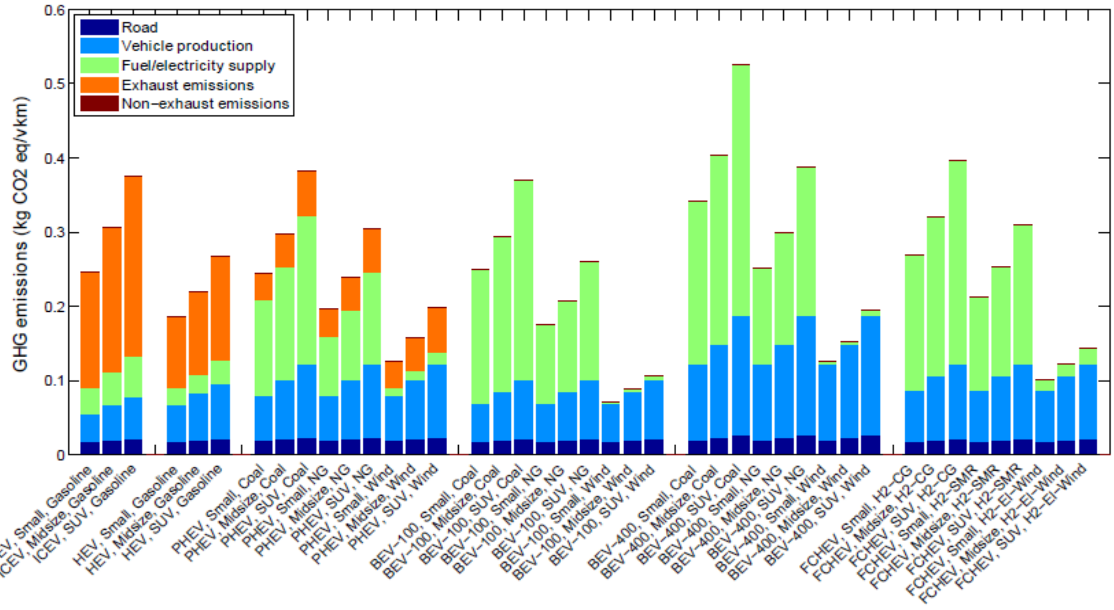
Source: (PSI/EMPA/ETHZ, 2016)

It is also evident from both figures that the type and source of fuel or electricity is an important factor determining the relative burden for all powertrain types. Figure A2 above shows the BEV powered by electricity obtained from wind has the lowest GHG impact, whereas the coal-fired BEV not only has the worse carbon footprint among all BEVs considered but also emits as much as the ICEV. Similarly,

Figure A3 demonstrates that the FCEV has a lower burden when the hydrogen is produced from electrolysis (based on the Swiss mix) compared to the hydrogen from steam methane reforming of natural gas. The fuels used by the ICEV also determine the magnitude of its emissions: as expected, petrol cars are found to generate higher GHG emissions compared to diesel cars; natural gas seems to allow for the lowest GHG emissions from ICEVs. Section A1.1.3 addresses alternative fuels in more detail, examining the environmental impacts of fuel production.

We have also considered the variability in impacts due to differences in vehicle sizes. Whilst the results above compare impacts between powertrain and fuel types for the same vehicle type, size/weight /segment is an important factor affecting the environment performance of vehicles (Frischknecht and Flury, 2011 – cited in (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)), even without accounting for potential variation in the typical/average lifetime mileages for different segments. As Figure 2.9 illustrates, heavier and larger vehicles generate higher GHG emissions for the same lifetime mileage regardless of the powertrain and fuel type, due to higher fuel consumption and emissions during vehicle production.

Figure A4: Life cycle GHG emissions for different vehicle sizes



Source: (Hofer, Simons, & Schenler, 2013)

It follows that the magnitude of impacts is also expected to differ between **different vehicle types** (passenger cars, vans HGVs, busses), due to differences in weight and operational energy consumption between these vehicles but also due to the differences in assumptions of lifetime mileages associated to the use of these vehicles (i.e. commercial vehicles tend to have higher average lifetime mileages). The specific operational duty cycle is an important factor in assessing overall impacts, e.g. environmental 'payback' for higher production emissions for a battery electric taxi will be much faster due to their higher annual mileage compared to average private car use for similarly sized vehicles.

In addition to GHG emissions, **other environmental impacts** are assessed by the literature, though to a lesser extent. Similarly, these studies also focus mainly on passenger cars.

In terms of impacts associated to airborne pollutants (e.g. TAP, POCP), (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) argue that the level of GWP is a good indicator of contribution to all other environmental impacts. In line with this finding, literature (e.g. (Helmers & Weiss, 2017), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)) shows that BEVs perform better than ICEVs in terms of **POFP**. The results of **TAP** impacts however appear to vary with the study – some studies conclude that the BEV has a worse environmental performance than the ICEV (due to the coal-based electricity supply chain – see (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)) as opposed to others which find similar impacts (stemming from the production of materials for the powertrains - although the authors indicate that there is a difference in the materials used and thus the source of impacts between the conventional and electric powertrains – see (Hawkins et al, 2012)). Others show the BEV performing better than the

ICEV that exhibits higher burdens in their fuel supply chain ((PSI/EMPA/ETHZ, 2016), (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)). On the other hand, FCEVs are found to exhibit a worse performance than the ICEV due to their production and fuel supply chain ((Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)). xEVs also appear to contribute more significantly to **PMF** as compared to ICEV linked to the use of coal in the production of electricity but also from the production stage ((Bauer, Hofer, Althaus, Simons, & Del Duce, 2015), (Hawkins et al, 2012)). More detail on the contribution of the different stages to overall impacts is provided in the next section.

The fuel type also affects the magnitude of the **TAP** and **PMF** impacts. Electricity produced from hard coal and lignite combustion, for example, is expected to emit higher levels of SO_2 (and other pollutants) and thus lead to a higher environmental burden (Hawkins et al, 2012). The use of natural gas to produce electricity on the other hand is associated with lower impacts. (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015) also shows that the CNG vehicle performs better compared to the diesel and petrol equivalent vehicles in terms of **TAP** and **PMF** – but also **POFP** and **HTP**.

In terms of **resource use**, the BEV can generate higher impacts than the ICEV in terms of water and metal depletion, urban land occupation and mineral resource depletion linked to the production of the battery and/or electric powertrain (Helmers & Weiss, 2017). Regarding toxicity impacts, the BEV is also found to generate higher **HTP impacts** than the ICEV due to its production and fuel supply stages ((Helmers & Weiss, 2017), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)).

In summary, whilst it is clear which fuel type (natural gas) and electricity sources (produced from renewable energy) can achieve the lowest overall environmental burden, the powertrain type which exhibits the best environmental performance depends on the impact category: the xEVs can perform better than the equivalent ICEVs over its entire lifecycle when considering GHG impacts, but this advantage becomes less clear when assessing other environmental impacts as it is highly dependent on other factors (such as the electricity mix, battery production location, etc). The discussion on the relative importance of the different lifecycle stages presented in the following section helps shed further light on these results. Differences between vehicle sizes and types are mainly related to their weight and lifetime mileage.

A1.1.1.4 How do different impacts vary over the vehicle lifecycle?

As before, we first focus our analysis on GHG impacts from passenger cars given their extensive assessment in the literature.

The literature shows that the WTW cycle, in particular the use phase (TTW), contributes to the highest GWP impact from the ICE passenger car (i.e. due to exhaust emissions) (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015). In the case of BEVs and FCEVs, both the equipment cycle and the WTT cycle dominate their GHG impacts.

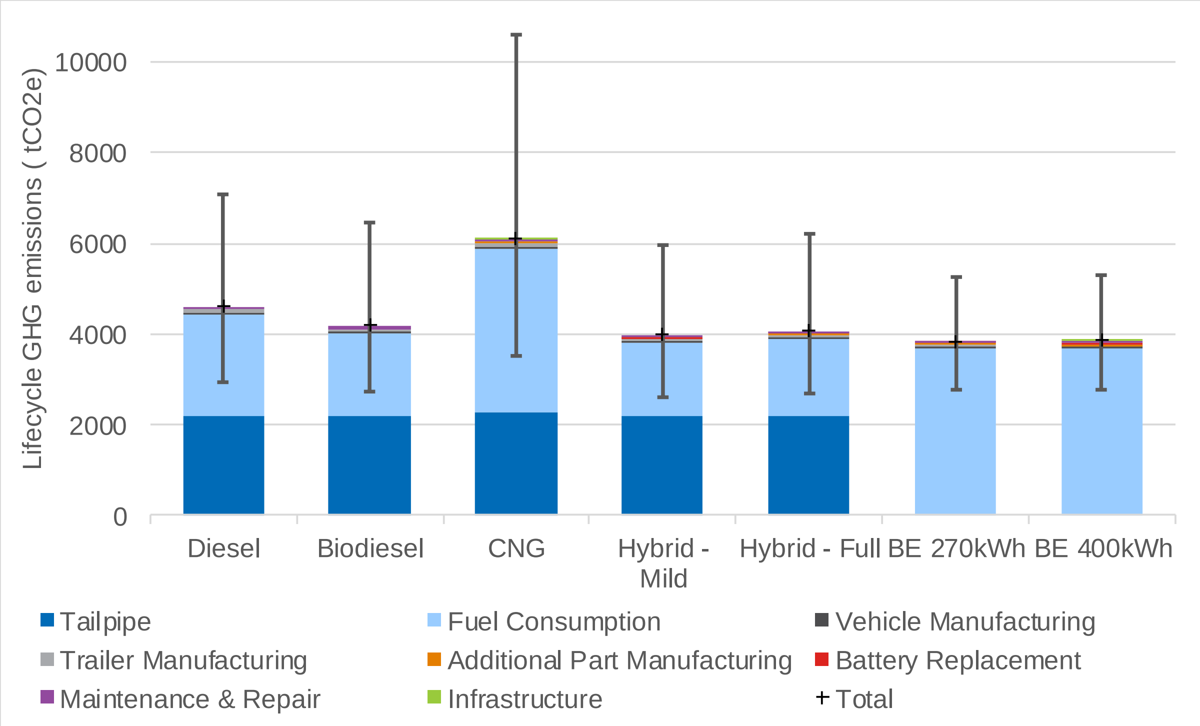
We find that the relative importance of EVs' lifecycle stages largely depend on the source of electricity and hydrogen production (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015). Figure A3 above demonstrates that for renewable sources of energy, both BEVs and FCEVs generate lower emissions during their WTW cycle (i.e. from fuel supply) and therefore the equipment cycle (i.e. its vehicle components) becomes more relevant.

The choice of fuel powering the ICEV also affects the relative contribution of its lifecycle stages, although not to the same extent as it was found for EVs. Figure A3 also shows that the use of natural gas leads to lower impacts in the use phase (TTW) but also in the fuel supply stage (WTT) and thereby increases the relative burden of the equipment cycle (differences in production impacts between ICEVs powered by different fuels are minimal).

No significant differences between the relative importance of lifecycle stages in terms of impacts from different vehicle classes/sizes have been found, i.e. same stages have a similar relative impact regardless of vehicle size (as percentage of total lifecycle impacts). However, if the assumptions on lifetime mileage differ between vehicle sizes, this also leads to differences between the relative share of the lifecycle stages of vehicles with varying sizes.

The relative burden of lifecycle stages is also found to differ by **vehicle type**. It is apparent from the literature that the use phase (TTW) or the fuel/electricity supply stage (WTT) (the latter in the case of EVs) tend to dominate the share of overall of impacts from HDVs (Figure A5) due to the higher lifetime mileage inherent to the role of these vehicles. Figure A5 shows that fuel consumption and tailpipe emissions are the main contributors to total life-cycle GHGs emissions for trucks. GHG impacts in the fuel consumption stage result from natural gas manufacturing for CNG, petroleum refineries for diesel and electricity generation for electric powertrain vehicles.

Figure A5: Life cycle GHG impacts from trucks



Source: (Sen, Ercan, & Tatari, 2017)

Unlike GHG impacts, **other environmental impacts** tend to be more strongly linked to production or fuel pathways and less so to the use phase even in the case of ICEVs. Similarly, results are mainly reported for passenger cars.

The production of materials required for the manufacturing of vehicles and the fuel/electricity supply chain are responsible for significant **TAP and PMF impacts** from both conventional and electric powertrains ((Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) , (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015), (PSI/EMPA/ETHZ, 2016)). According to (PSI/EMPA/ETHZ, 2016), even in the case of ICEVs, exhaust emissions are only found to contribute to 10% of the total PMF - road and vehicle glider production and the fuel production chains represent more significant sources. However, the location of emissions is also an important consideration for impact of the pollutant. The PMF tailpipe emissions are more likely to be in proximity to people (i.e. in cities), while emissions from industry are often away from populated areas. **POFP** impacts are mainly due to combustion and blasting in mining activities (Hawkins et al, 2012), roads, vehicle production as well as fuel supply chains (PSI/EMPA/ETHZ, 2016). Similarly, exhaust emissions (NOx and NMVOC) from ICEVs represent only 20% of the overall POFP impact of the diesel vehicle.

In terms of **resource use**, the equipment cycle of the BEV is the most resource-intensive stage (due to reliance on metals) whilst the WTW cycle of the ICEV is an important resource consumption stage (in terms of fossil fuel energy) (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)), (Hawkins et al, 2012).

The production and fuel supply stages are also the main source of impacts for BEVs and ICEVs in terms of **HTP** (Hawkins et al, 2012). According to (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) , the equipment cycle dominates for both powertrain types. Similar results are found for the FCEV where its production process and that of hydrogen are the main contributors to **HTP** impacts (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015).

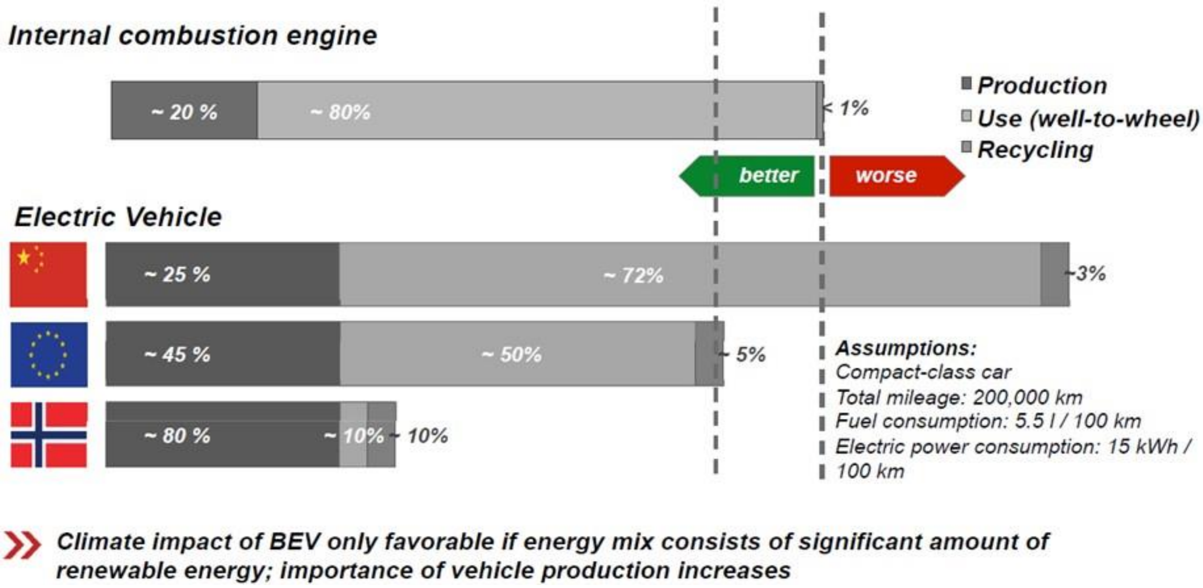
Finally, it is worth noting that end-of-life treatment impacts are not found to be significant for any impact category (Hawkins et al, 2012). This however could also be related to modelling and data choices and assumptions. A more in-depth discussion of end-of-life impacts (including recycling) is presented in Section A1.1.2.

In summary, whilst the relative importance of the lifecycle stages varies with powertrain and impact category, the electric passenger car production stage is generally responsible for a higher absolute burden compared to ICEV for all impact categories. In this context, the results from the previous section become clearer: the overall impact of the xEV can be lower than that of an equivalent ICEV, if and only if, it can achieve lower impacts in its WTW cycle that compensate for the additional burden in the production stage. This varies between studies and is dependent on certain assumptions as explored in the following section.

A1.1.1.5 What key assumptions determine the overall impacts of vehicles?

As highlighted above, the **carbon intensity of the electricity and hydrogen** depends on the source of energy used and largely determines the magnitude of the xEV impact. It follows that the electricity mix of the region where the vehicle is mainly used will be a key factor. Figure A6 demonstrates the variation in impacts from the electric vehicle depending on whether the electricity was obtained in China, the EU or in Norway. In the case of China, the impact from the WTW cycle is such that the overall impact of the xEV becomes greater than that for the equivalent ICEV due to the higher carbon intensity of electricity in that country. In addition, the relative importance of the lifecycle stages also changes accordingly. **Geographical considerations** are thus an important aspect to take into account when performing an LCA, as well as changes that might occur over future years (for example even over the life of the vehicle the electricity mix might change significantly).

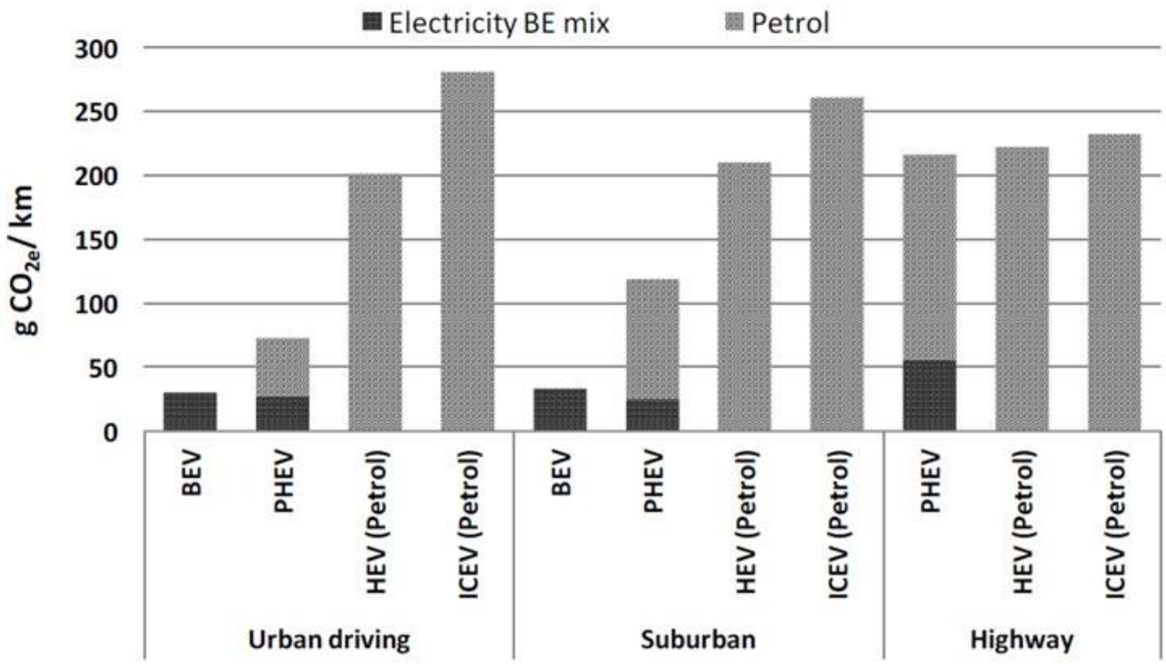
Figure A6: Audi LCA - impact of different electricity mixes on CO_2 emissions from a passenger car



Source: (Audi, 2013)

Related to the above, other **spatial considerations** also affect the results, such as the type of roads where the vehicle is used. The relative performance of EVs and ICEVs is found to vary according to the assumed **driving conditions**. Figure A7 shows that differences between powertrain types are greater in the case of urban driving conditions with electrified powertrains exhibiting a better environmental performance. Differences are, however, less pronounced for highway driving. This is in part linked to the traffic and congestion conditions inherent to each context: urban driving is associated with more stops where EVs have an advantage compared to ICEVs (due to regenerative breaking and start and stop capabilities) ((Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014), (Messagie, 2017)). No similar studies were found on the performance of FCEVs; however, the effects would be expected to be similar due to the electric drivetrain.

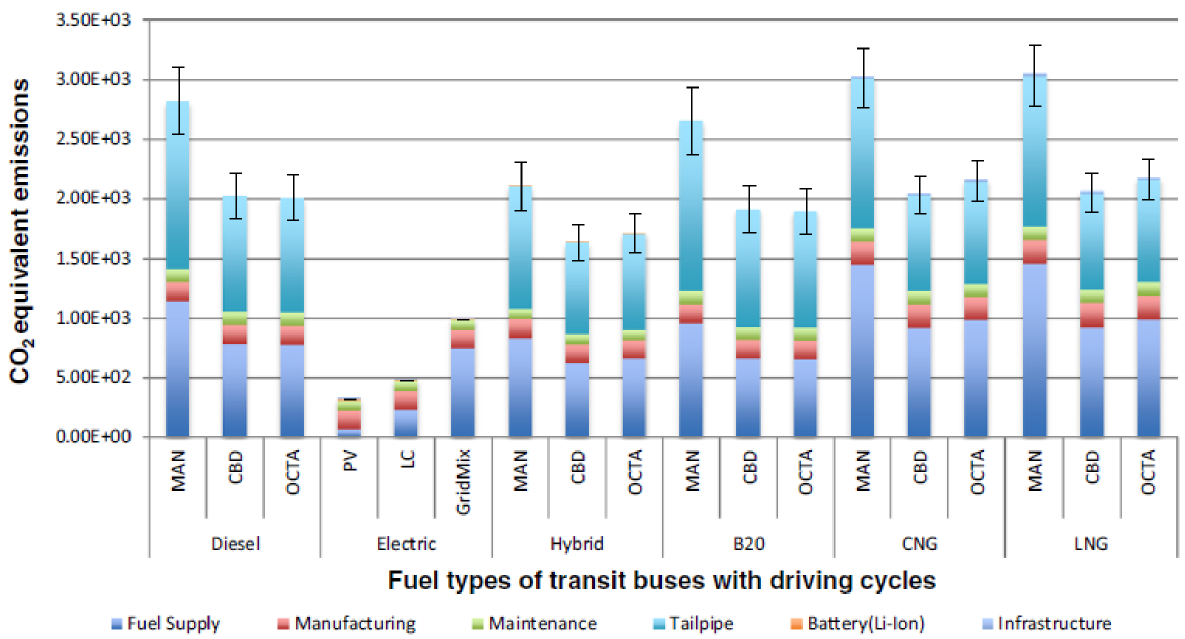
Figure A7: Impact of driving conditions on WTW GHG emissions from passenger cars



Source: (Messagie, 2017)

A similar variation in results due to differences in speeds and stops is found for transit buses as Figure A8 demonstrates. The driving cycle with lower operation speed and more stop-and-go leads to higher emissions, particularly in the case of CNG and LNG buses. The three driving cycles presented in the figure are Manhattan (MAN), Central Business District (CBD), and Orange County Transit Authority (OCTA). The MAN cycle has the lowest average speed and represents driving in congested urban areas. The CBD cycle is laboratory-defined cycle with even stop frequencies and even acceleration and deceleration rates, rarely seen in real-time operation. The OCTA cycle has medium speed urban/suburban operations and represents the most realistic fuel economy data.

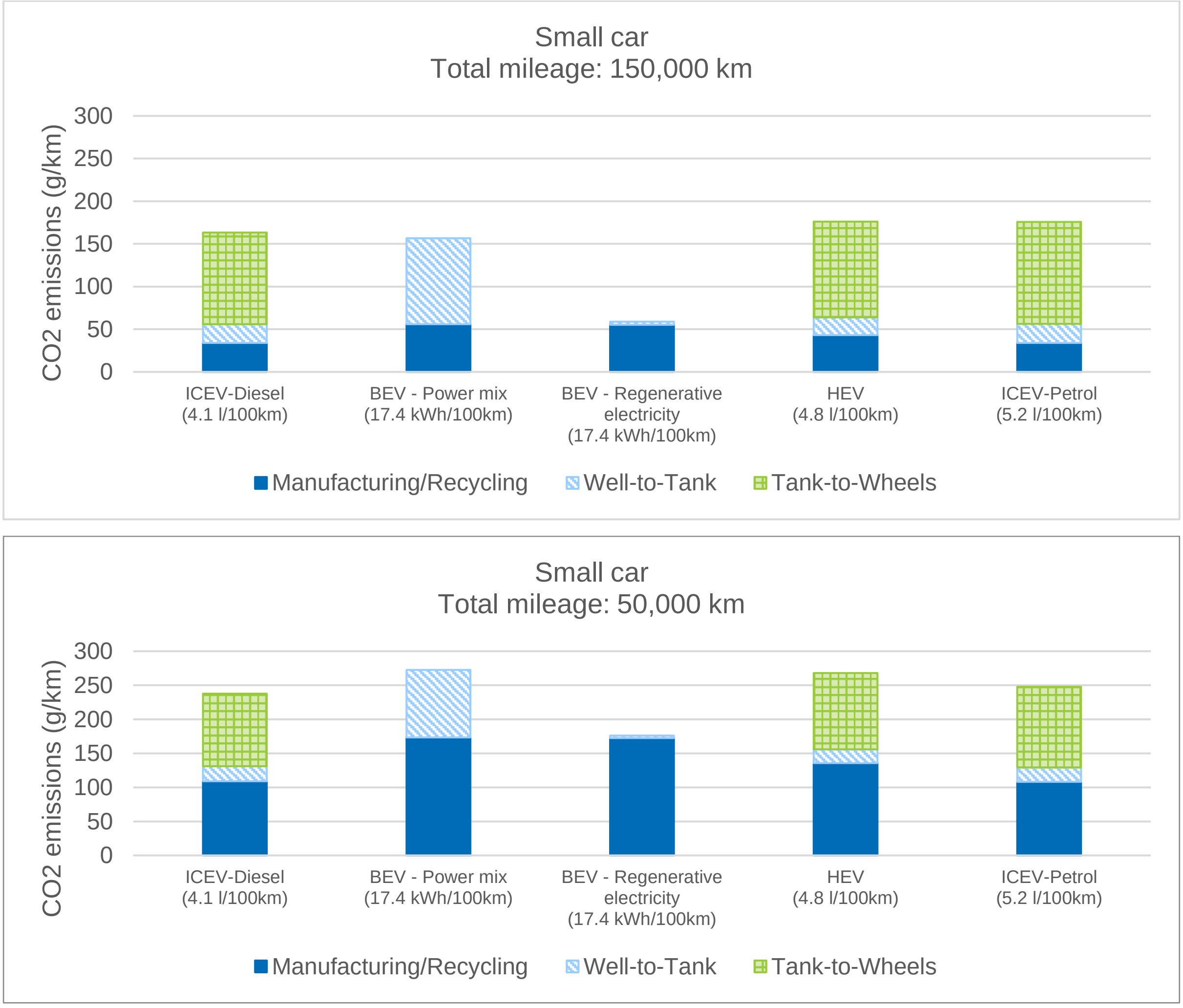
Figure A8: Impact of driving cycles on life cycle CO_2 emissions from buses



Source: (Ercan & Tatari, 2015) Notes: The three driving cycles presented are Manhattan (MAN), Central Business District (CBD), and Orange County Transit Authority (OCTA). Powertrain and fuel sources considered are: diesel, electric (including a photovoltaic (PV), low carbon (LC) and national electricity grid mix (GridMix) scenarios), hybrid (diesel-electric), biodiesel (B20), compressed natural gas (CNG), and liquefied natural gas (LNG).

Lifetime mileage is another key factor determining the emissions from the vehicle lifecycle when the functional unit is expressed in terms of km driven (vehicle-kilometre, passenger-kilometre or tonne-kilometre). Figure A9 demonstrates that for a higher lifetime mileage (top chart) the difference between the BEV, HEV and ICEV increases, with the BEV offering a higher advantage in terms of reduced GHG emissions. It is anticipated that a longer lifetime mileage allows the initial one-off production impacts to be distributed over a longer period – this tends to favour particularly BEVs which are expected to have higher production impacts (see Section A1.1.2 below for a detailed discussion on the equipment cycle impacts).

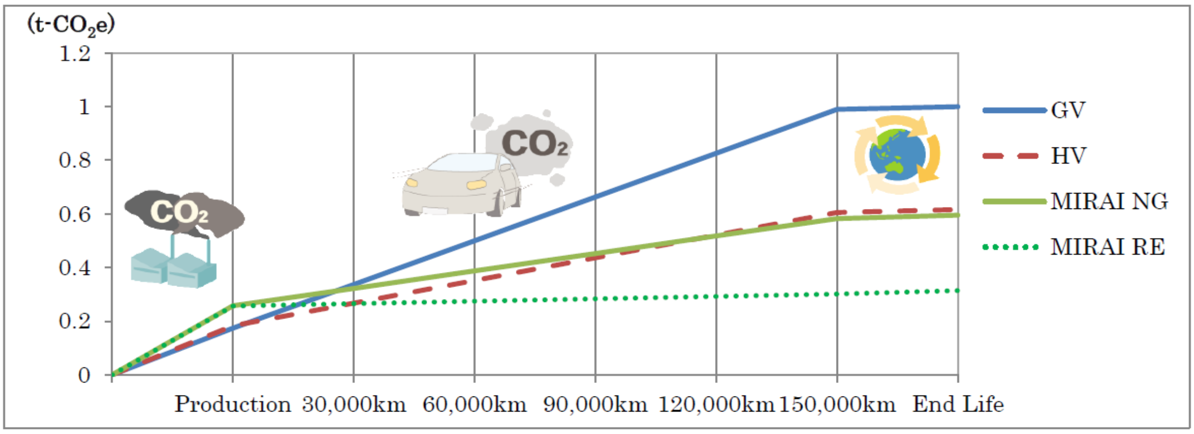
Figure A9: Impact of lifetime mileage on GHG emissions from passenger cars



Source: Reproduced from (ADAC, 2018)

In the case of FCEVs, the study conducted by Toyota for its hydrogen-powered vehicle, the Mirai, also shows that the GHG emissions of the FCEV break-even with the emissions from the equivalent petrol car around 20,000 km or earlier depending on the source of hydrogen (Figure A10) and thereby the choice of lifetime mileage when reporting impact per km driven is also expected to affect the relative burden of FCEVs compared to ICEVs.

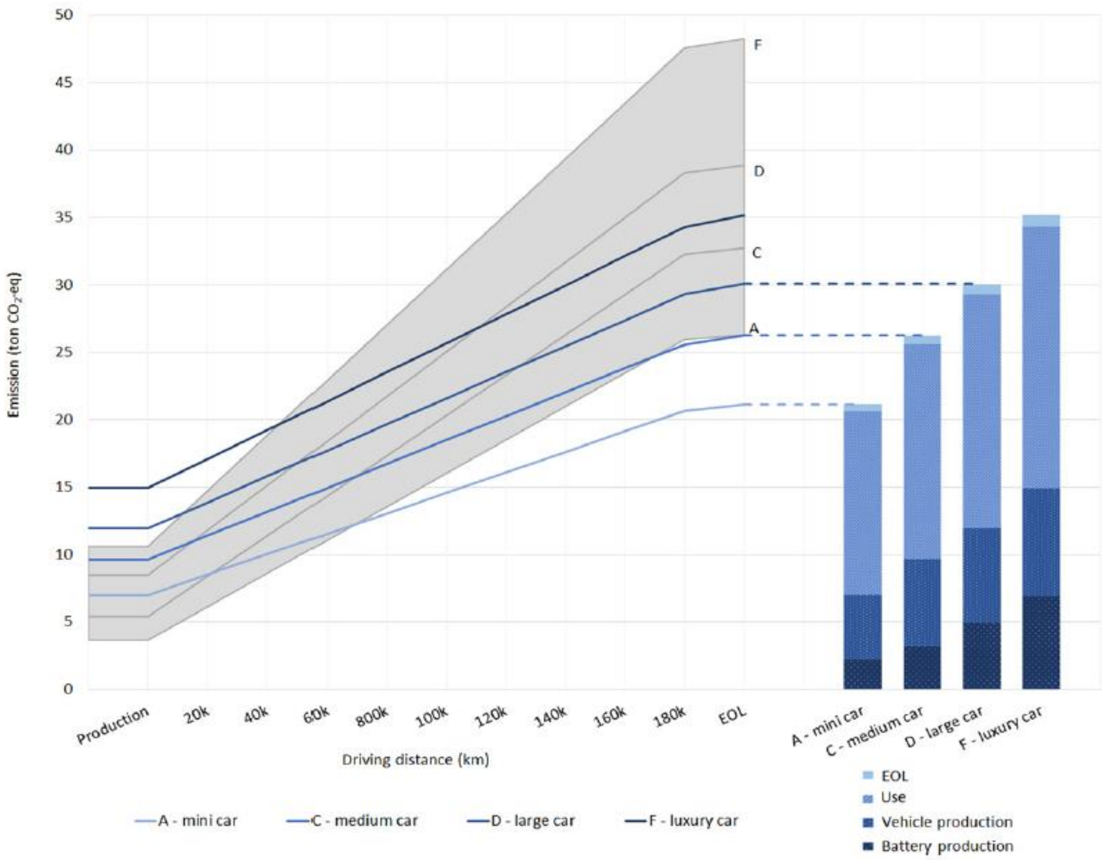
Figure A10: Sensitivity of FCEV to lifetime mileage (GV: gasoline, HV: hybrid)



Source: (Toyota, 2015)

The choice of lifetime mileage is equally important when assessing impacts between vehicles of different sizes. Figure A11 illustrates that the larger BEV can break-even at lower mileage (i.e., the driving distance at which the blue lines representing the performance of BEVs cross the grey-shaded areas representing the performance of conventional vehicles is lower for larger segments).

Figure A11: Life cycle GHG emissions for different vehicle classes



Source: (Ellingsen, 2016). Notes: The chart on the left represents the overall emissions (for the entire lifecycle of the vehicle) – the areas in grey represent the lifecycle GHG emissions of the conventional vehicles for all the segments included; the blue lines present the lifecycle results for EVs.

Another source of differences in impacts concerns the uncertainty regarding characterisation factors for toxicity impacts (Hawkins et al, 2012), (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)). These factors are used to quantify how much impact a product or service has in the different impact categories.

To a lesser extent, uncertainty around resource use is also a source of variation (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014). In addition, the approach in accounting for future changes is expected to affect the extent of impacts as discussed in the following section.

A1.1.1.6 How might future changes affect different impacts?

Only some studies consider future changes and perform sensitivity analysis to assess their effects (e.g. (PSI/EMPA/ETHZ, 2016), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015), (ANL, 2016)). Others discuss the potential for future changes and their impact for the model parameters. In summary, the literature identifies the following changes and elaborates on their expected impacts:

- Carbon intensity of electricity mix in Europe expected to fall (switch from coal to natural gas and renewable energy) (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015).
- Fuel/electricity efficiency expected to improve ((Bauer, Hofer, Althaus, Simons, & Del Duce, 2015), (Hawkins et al, 2012), (PSI/EMPA/ETHZ, 2016)).
- Vehicle mass anticipated to decrease due to the use of lightweight materials (PSI/EMPA/ETHZ, 2016).
- EV technology and production process is developing rapidly ((Helmers & Weiss, 2017), (Hawkins et al, 2012)) - environmental performance data becomes obsolete quickly (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) and will affect future parameters such as: battery size, capacity, chemistry and lifetime.
- Expected benefits of scale and technological improvements in production of materials and manufacturing of EVs (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014).
- Potential for second-life applications of batteries (Helmers & Weiss, 2017).
- Potential for V2G applications (Helmers & Weiss, 2017).

If realised, these expected changes present the opportunity to achieve further GHG emission reduction for all vehicle technologies by 2030 (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015). In the case of BEVs in particular, lower emissions from electricity mix will reinforce this effect in the long-run, minimising their impacts in terms of GHG emissions, TAP and PMF; however the same decrease is not expected for FCEVs as the majority of TAP and PMF burdens are due to emissions from mining of platinum (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015). HTP impacts from BEVs and FCEVs are still expected to remain higher in the future although decreasing.

The impact estimates discussed throughout this section are very much interlinked to the specificities of both the equipment cycle and the WTW cycle: the following sections discuss these in more detail.

A1.1.2 Vehicle production, maintenance and end-of-life

This section focusses on the impacts stemming from the production, maintenance and end-of-life (EoL) stages, that is, the equipment lifecycle. We assess the main impacts reported in literature in terms of the emissions embedded in the vehicle and attempt to understand the underlying processes and causes for the observed variations by vehicle and powertrain, as described above. It thus complements the previous section by providing further insight into the impacts of specific components or production processes.

We note that some LCA studies identify the source of impacts by vehicle component (rather than by the abovementioned stages). Impacts from the production, maintenance and disposal stages are understood to include the impacts from powertrain, base vehicle or glider (vehicle without the powertrain and traction battery) and the traction battery.

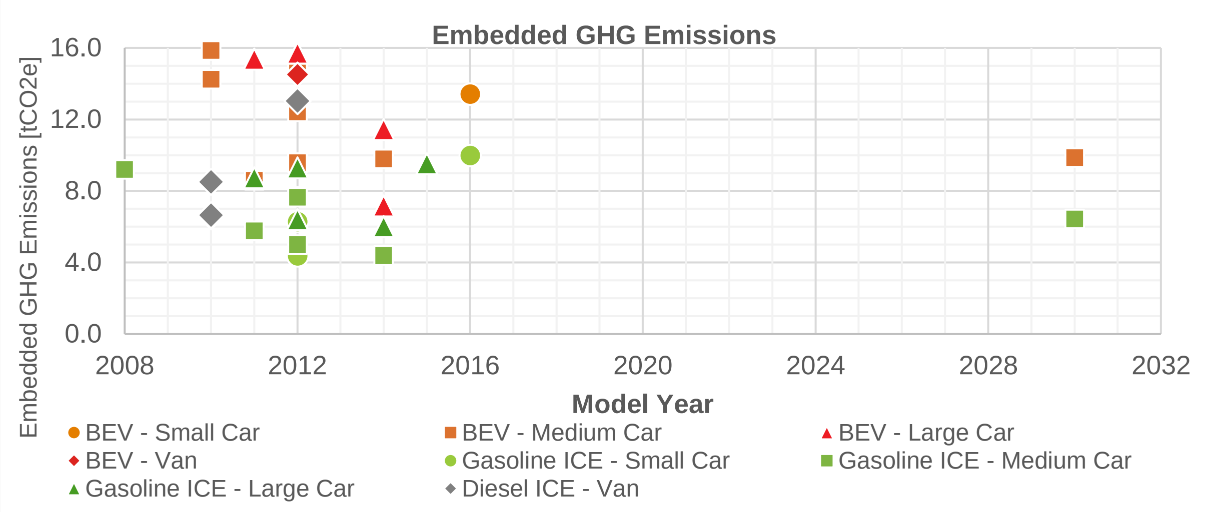
As before, we look first at GHG impacts from passenger cars, as these are widely covered by the literature, followed by a discussion for other vehicle types and environmental impact categories.

A1.1.2.1 How and why do the GHG impacts from the equipment lifecycle differ between powertrain and vehicle types?

As highlighted earlier, although the WTW cycle is an important source of GHG emissions for both the conventional and electric powertrains, electrification is found to increase the impact from the equipment lifecycle. When comparing the two extremes (ICEV vs BEV), the results from a selection of the published literature illustrated in Figure 2.10 show that embedded GHG emissions from vehicle production and end-of-life tend to be higher for BEVs compared to ICEVs. Similarly, 85% of the studies

(Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) reviewed covering the whole vehicle lifecycle find that electrification is associated with higher impacts from the equipment lifecycle.

Figure A12: Embedded GHG emissions reported by the literature



Source: Ricardo, compiled from the literature.

On the other hand, differences between the production of the conventional and natural gas powertrains are expected to be minimal as discussed above. The main difference to petrol /diesel powered vehicles is the gaseous storage, which does not have a significant impact.

The increased burden of the production stage in xEVs can be linked to the impacts from the supply chains for the production of electric powertrains and traction batteries, as also illustrated in Figure A13.

Figure A13: Previous Ricardo LCA of CO_2e emissions for (a) vehicle production by vehicle system, and (b) overall lifecycle impact

(a)

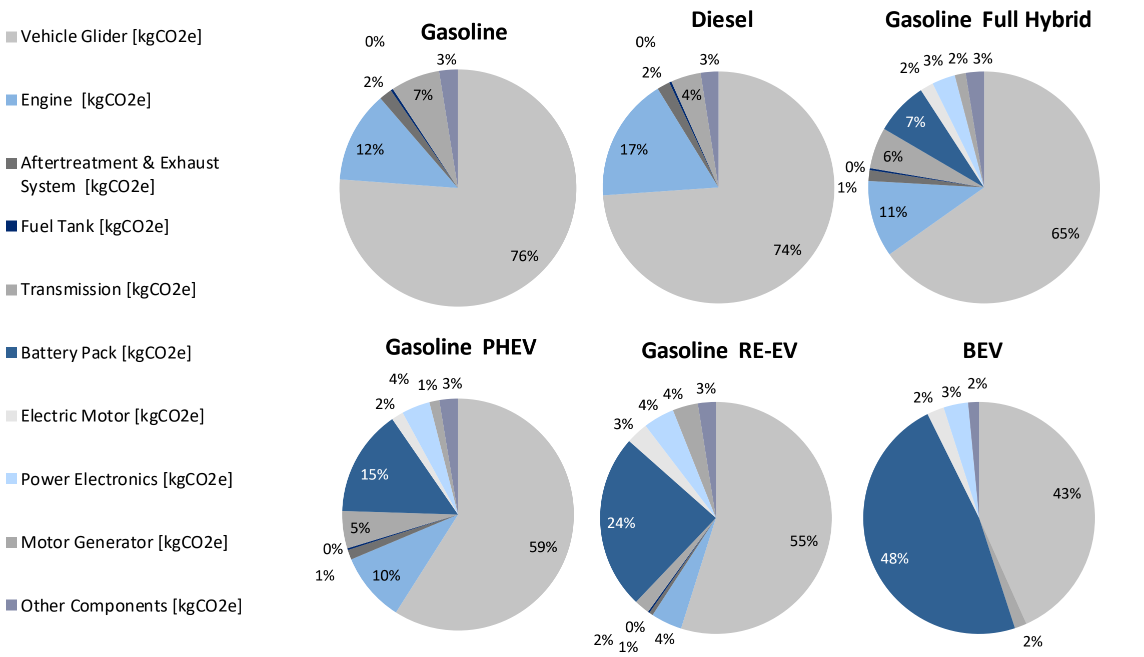
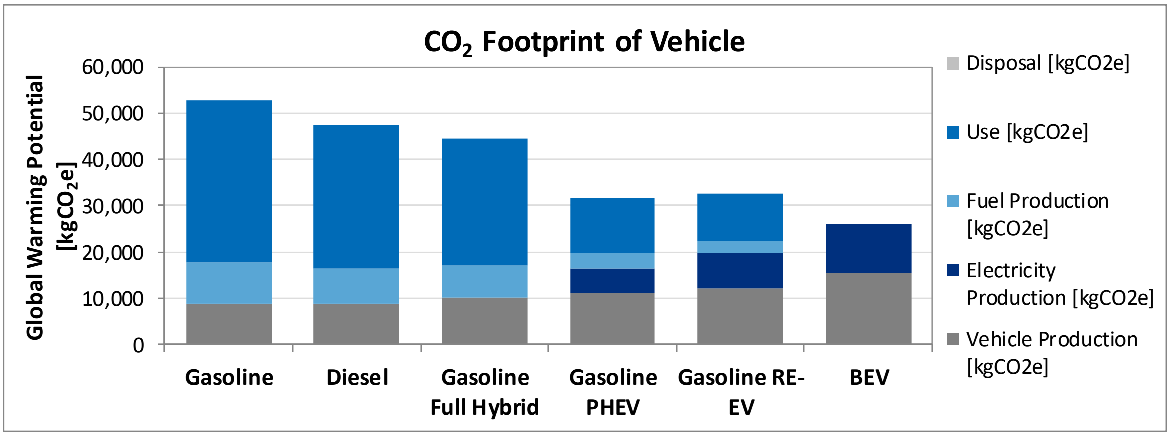


Figure A13: Previous Ricardo LCA of CO_2e emissions for (a) vehicle production by vehicle system, and (b) overall lifecycle impact

(b)

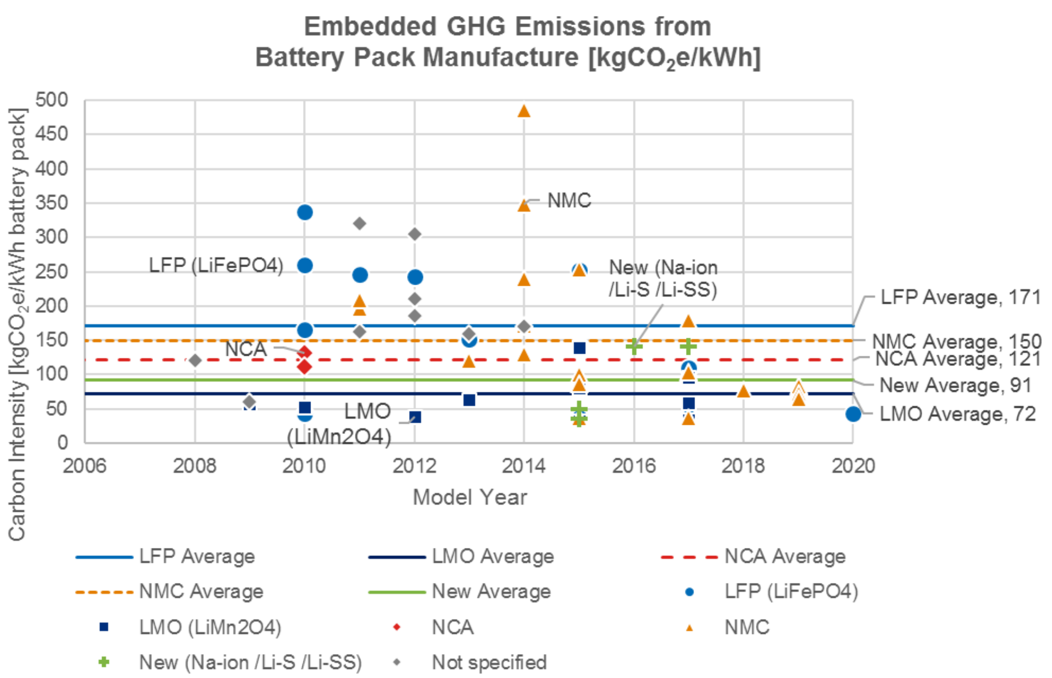


Source: Ricardo lifecycle analysis (Ricardo, 2011).

The **manufacturing of batteries**, in particular, is a key factor determining the magnitude of GWP impacts from BEVs (e.g. Majeau-Bettez et al. 2011 – cited in (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) , (Hawkins et al, 2012), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)). According to (Hawkins et al, 2012), 35-41% of the production GHG impact from the BEV comes from battery production, 7-8% from the electric motor and 16-18% from other powertrain components (inverters and the passive battery cooling system due to their high aluminium content).

There are, however, substantial differences in the estimates for impacts from battery manufacturing (see Figure A14), linked to differences in key assumptions. However, there is also a fairly clear downward trend visible in the available results when presented on a time-axis, with the most recent results based on more recent data based on EU manufacturing of NMC chemistry lithium-ion batteries published later in 2019 by (Kelly, Dai, & Wang, 2019) and (IVL, 2019) are significantly below the overall average from the literature.

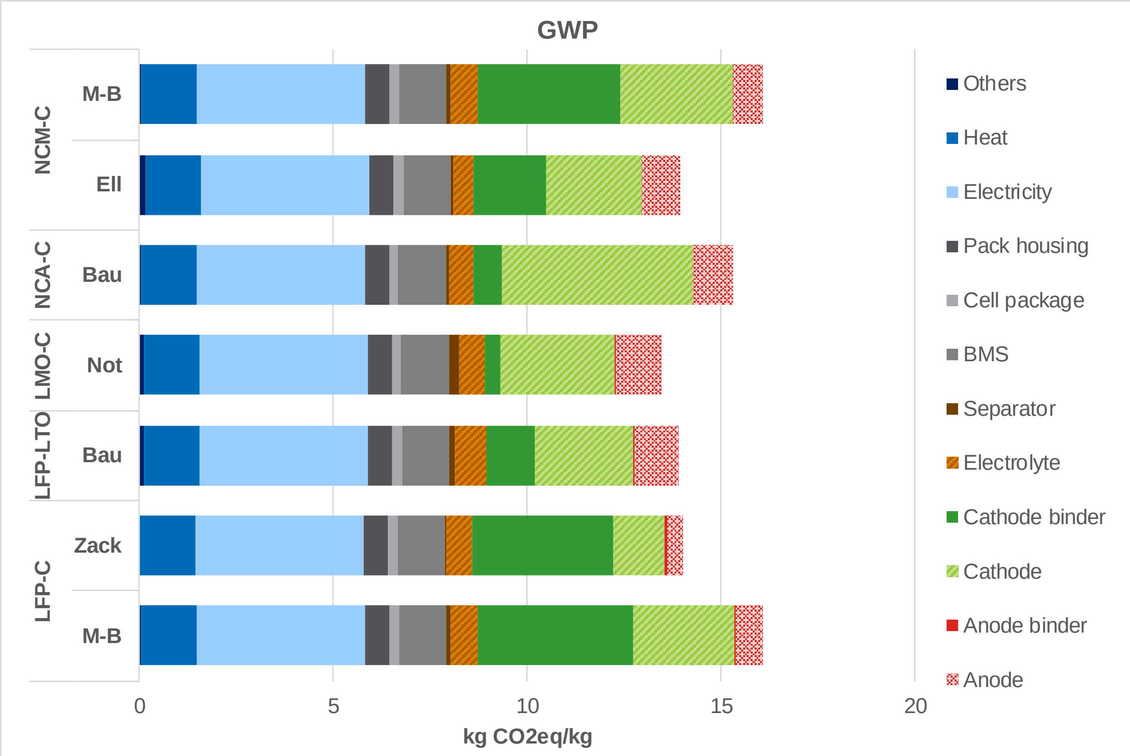
Figure A14: GHG impacts from battery production for different battery chemistries from the literature



Source: Ricardo, compiled from the literature. New chemistries include Li-SS = Lithium solid-state, Li-S = Lithium Sulphur, and Na-ion = Sodium-ion chemistries.

In an effort to provide a basis for comparison, (Peters, J. F., and Weil, M., 2018) normalised the results from several studies regarding different LIB (lithium-ion battery) cathode chemistries (Figure A15).

Figure A15: Estimated GHG breakdown of impacts (per kg battery) from the production of Li-ion batteries of different types: normalised estimates based on unified LCI datasets



Source: Reproduced from (Peters, J. F., and Weil, M., 2018).

Notes: NMC-C = NMC Cathode – Carbon (Graphite) Anode; similarly also for the other battery chemistries. Lithium-ion battery chemistries: NCM=NMC = Nickel:Manganese:Cobalt (Cathode), NCA = Nickel:Cobalt:Aluminium (Cathode), LMO = Lithium:Manganese Oxide (Cathode), LFP = Lithium Iron Phosphate (Cathode), LTO = Lithium Titanate (Anode)

Figure A15 shows that the energy required for battery production (particularly for dry room conditions and from electrode drying processes necessary to remove the NMP solvent) is expected to contribute around 35-45% of the embedded GWP of an automotive Li-ion battery (LIB) pack (depending also on the source of this energy). Regarding the battery components, the Cathode and Cathode Binder contribute the most to the embedded GWP of a Li-ion battery pack. On the other hand, differences between different chemistries for Li-ion per kg of battery are anticipated to be relatively small in terms of GHG impacts.

The source of the energy used in the production stages is also an important factor for GWP impacts and different configurations seem to be currently operated. While using natural gas directly is the most GHG and energy efficient (and the least costly) source of heat/steam (compared to grid electricity mixes still with significant conventional thermal generation), electricity is also used, especially when it is available from low carbon (renewable) sources. An update of the GREET model in 2018 presented data on the precursor and cathode material production processes, showing the use of both electricity and gas (Dai Q. K., 2018). The authors collected data from a manufacturing plant that could produce LCO and NMC from precursor materials, following the standard two step calcination process for cathode materials used for traction applications. The plant is exclusively powered by electricity, almost all of which is used in the calcination kiln. Electricity consumption by other equipment is negligible, by comparison. The report also refers to a second plant that produces the NMC and NCA precursors. It is assumed that the precursor production process is 100% powered by steam, which is used for alkali pre-treatment, reactor heating, ammonia stripping, and evaporation. The steam is supplied by a local power plant and assumed to be generated using natural gas. Similarly, for the 2017 update to the GREET model information was gathered from two leading Chinese LIB manufacturers on the electricity and natural gas consumption in NMC LIB cell manufacturing process (Dai, Dunn, Kelly, & Elgowainy, 2017).

In those facilities, electricity is primarily used to power 11 dehumidifiers and 4 industrial water chillers for process cooling, and the electricity consumption by the rest of the equipment is negligible. However, dry room operation (i.e. dehumidification and cooling) and electrode drying (and NMP recovery) are the biggest contributors to energy consumption for LIB manufacturing, and for these, heat from steam is used. In comparison, the Product Environmental Footprint Category Rules (RECHARGE, 2018) for batteries assumes all energy in the production stages is provided by electricity.

In addition to the form of energy used, the scale and utilisation of the manufacturing facility can be another source of variation in the data reported on energy usage. Analysis in a recent report estimates energy usage for two large-scale battery cell facilities that are lower than previous studies (Kurland, 2019), at between 65-50 kWh_{elec} per $kWh_{battery}$.

Our analysis for the JRC (Ricardo Energy & Environment, 2019) also revealed the relevance of geographical considerations for battery manufacture associated to the GHG intensity of the energy source used in manufacturing, and in the production of key materials. Similarly, (Helmers & Weiss, 2017) finds that the electricity consumption to produce batteries in China can dominate the lifecycle impacts from the BEV.

Moreover, differences are also apparent between the smaller Li-ion batteries used in HEVs and PHEVs, compared to those in BEVs. It is expected that overall impacts per kWh of energy storage for these batteries are higher than for BEVs given that the larger packs in BEVs allow the use of chemistries that are more optimised to improving energy density - whereas the smaller packs in PHEVs and HEVs need to have much greater power density[34] in addition to their battery packaging, battery management system, etc., which represent a larger overall share of the total pack mass relative to the battery cells in these hybrid powertrains. Nevertheless, we have not found specific analysis of this aspect in the literature. Overall, the absolute impacts from batteries are still substantially smaller for PHEVs and BEVs.

A further consideration for xEV batteries are the impacts of chemistry improvements and changes due to technological and process changes. For example, improvements to battery energy density reduce the amount of material (and energy) required to make batteries. In addition, LCA studies of new battery chemistries (e.g. solid-state batteries, sodium-ion chemistries, and lithium sulphur batteries) suggest that the impacts across a range of environmental impact categories could be substantially reduced. When considering impacts in a medium to long term (i.e. 2030-2050) horizon, it would therefore be important to account for such considerations.

In the case of FCEVs, the equipment lifecycle is also found to be an important stage as discussed above. (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015) suggests that the emissions associated to the **production of the fuel cell** lead to higher impacts from the production stage of FCEVs. Similarly to batteries, improvements to fuel cell technology/design and manufacturing in the future is expected to have significant impacts on these.

As with passenger cars, the analysis by (Sanchez, Martinez, Martin, Holgado, & Morales, 2013) shows that the equipment lifecycle becomes more relevant as a source of GHG emissions for the electric bus compared to the equivalent ICEV, HEV and FCEV due to the maintenance process. Similarly, the battery packs are responsible for a higher burden of the electric trucks compared to the diesel truck (Lee & Thomas, 2016).

A1.1.2.2 How might future changes in materials and energy sources affect GHG impacts?

A1.1.2.2.1 Materials

In addition to changes in the actual materials used in vehicles (e.g. due to weight reduction, or battery chemistry changes), a reduction in the impacts from raw materials is also anticipated in the future due to broad decarbonisation of industry, transport and energy. Within Europe industrial emissions are capped under the EU ETS and with the Commission's objective of economy-wide climate-neutrality by 2050, the impacts from key battery materials produced in Europe, such as steel and aluminium are to reduce significantly. The rates of improvement in the decarbonisation of materials is likely to occur at different rates in different regions, which creates an element of uncertainty in the overall trends for battery manufacture depending on the region of manufacture and the sourcing of these materials.

[34] Energy density describes how much energy the device can store for a given mass, while power density describes how quickly the device can deliver energy. For a hybrid vehicle, its ability to deliver energy is more important than its ability to store energy.

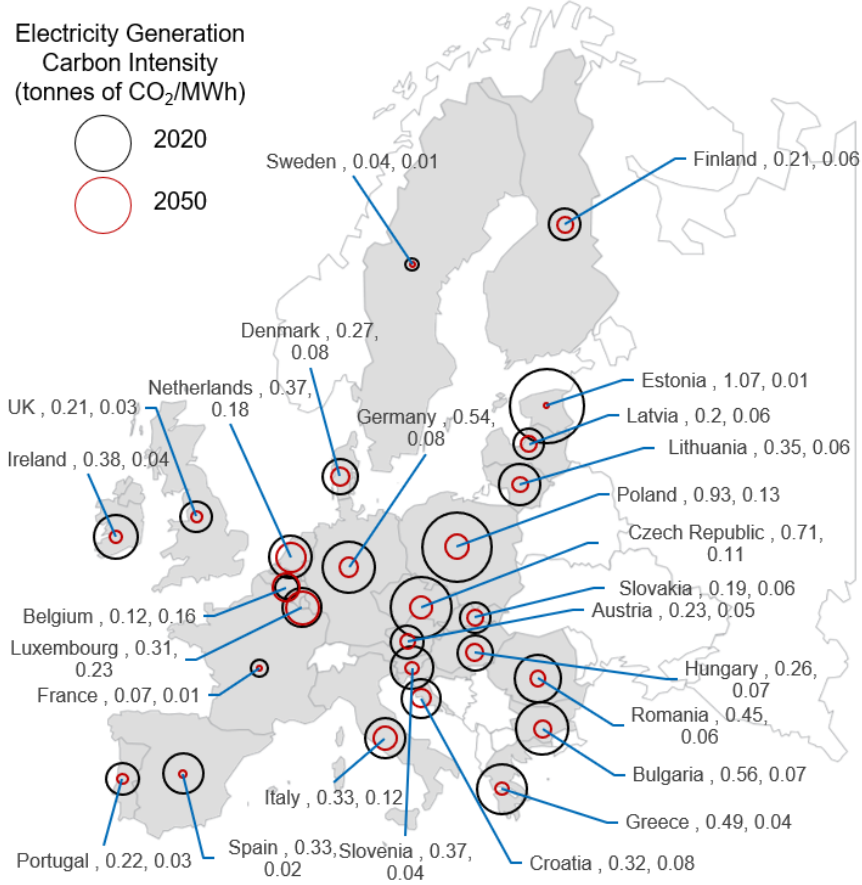
Recent analysis presented in (ECF, 2018) also indicates that the emissions intensity of EU steel and plastics production could halve by 2050, and that aluminium manufacturing emissions could be reduced even more through the use of low emission electricity generation. This is aligned with the ambition set by the EU's Long Term Strategy that proposes options for the transition towards a climate-neutral EU economy by 2050 in line with the objectives of the Paris Agreement (European Commission, 2018). Our preliminary analysis of datasets from the GREET model (ANL, 2018) and the SimaPro LCA model's Ecoinvent database show that process electricity use contributions to material production impacts can be significant in a range of other materials also, and so overall impacts will be influenced by changes in the future electricity mix.

The effects of such a transition would be two-fold, first they would act to reduce the impacts from the materials used in vehicle/component manufacturing. However, second, this would also potentially reduce the net benefits gained from recycling at the end of the battery's life, since the carbon intensity of the virgin material being displaced would be lower. Although this section has focussed on GHG impacts, it is worth highlighting that future changes in materials could also result in benefits in terms of other impact categories.

A1.1.2.2.2 Energy sources

The other major factor affecting the GHG impacts of vehicle/component production (and also recycling) is the GHG intensity of the energy used in these processes (accounting for 35-40% of the impact of battery manufacturing according to Figure A15). This is a major contributor to geographical variations in the production impacts of xEV batteries in particular, and makes the location of battery manufacture (and sourcing of energy) a particularly important consideration. However, in Europe, and also in other global regions, a transition to renewable and other low carbon power generation is ongoing. The following Figure A16 provides an illustration of current analysis of the 2020 and projected future GHG intensity of electricity generation in different European countries for the baseline scenario (used in this project's analysis). The GHG emissions from the EU electricity mix are anticipated to reduce by over 80% between 2020-2050 in the baseline case, and by over 90% for the Tech1.5 scenario (from analyses for the EU's Long Term Strategy (European Commission, 2019)). This will have a significant impact on the emission intensity of both vehicle and battery manufacture in Europe; though lower in other regions.

Figure A16: 2020 and projected future carbon intensity of grid electricity in different EU countries



Source: Ricardo analysis, comparing 2020 with 2050, based on European Commission modelling baseline as part of analysis for the Long-Term Strategy to reach a climate-neutral Europe by 2050 (European Commission, 2019).

A1.1.2.3 How does the equipment lifecycle contribute to other environmental impacts than GWP?

As discussed earlier, the equipment lifecycle appears to contribute more significantly to other environmental impact categories (compared to GWP impacts), in particular in the case of BEVs and FCEVs. The adverse impacts from EVs are linked to their supply chain where the mining for materials is responsible for substantial environmental burdens.

In the case of **TAP** impacts, the use of nickel, platinum, copper and to a lesser extent aluminium for batteries, the motor, the fuel cell system and/or the electrolyser creates an environmental burden in the production stage due to the SO_2 and NOx emissions from the metal mining and processing ((PSI/EMPA/ETHZ, 2016) , (Hawkins et al, 2012), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)). On the other hand, the production of platinum-group metals for the exhaust catalyst is the main source of TAP in the production stage of ICEVs. The authors of (Hawkins et al, 2012) note the impact from the platinum-group metals can vary significantly by geography of production.

Similar to TAP, the contribution of the BEV and FCEV production stage to **PMF** is associated to the mining of the same metals (nickel, platinum, copper and aluminium) ((Hawkins et al, 2012), (PSI/EMPA/ETHZ, 2016), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)). In terms of POFP impacts, it is the NOx emissions from blasting in mining activities which are found to create adverse impacts from the production of BEVs (Hawkins et al, 2012).

Regarding **resource use**, the reliance on metals for the production of BEVs explains their higher burden. (Hawkins et al, 2012) found that mineral resource depletion potential (**MDP)** impact of BEV is about 3 times than for ICEVs. However, the authors highlight high level of uncertainty in their analysis due to ReCiPe not having characterisation factors. Similarly, (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014) note that the production stage dominates **MDP impact** in the case of BEV.

Toxicity impacts are also heavily linked to the production process of both EVs and ICEV. As with resource use, BEVs exhibit a poorer performance in this impact category. According to (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014), the base vehicle (including the lead battery and maintenance) is responsible for the largest contribution to HTP for both ICEVs and BEVs. In addition, the electric powertrain (Li-ion battery, electric motor and power electronics) is also a major contributor in the case of BEVs, whereas the small electric starter motor and catalytic converters in the ICEV have also a meaningful impact (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014). Studies ((Hawkins et al, 2012), (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)) suggest that the additional burden from BEVs is caused by the use of nickel and copper whose production chain involve the disposal of sulfidic tailings. In the case of FCEVs, the authors of (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015) also indicate that the use of platinum in the manufacturing of fuel cells contribute to the release of toxic emissions.

Similar to HTP, the disposal of sulfidic tailings from the production chain of metals are a key contributor to **FEP** and **FETP** (Hawkins et al, 2012).

A1.1.3 Fuel cycle only

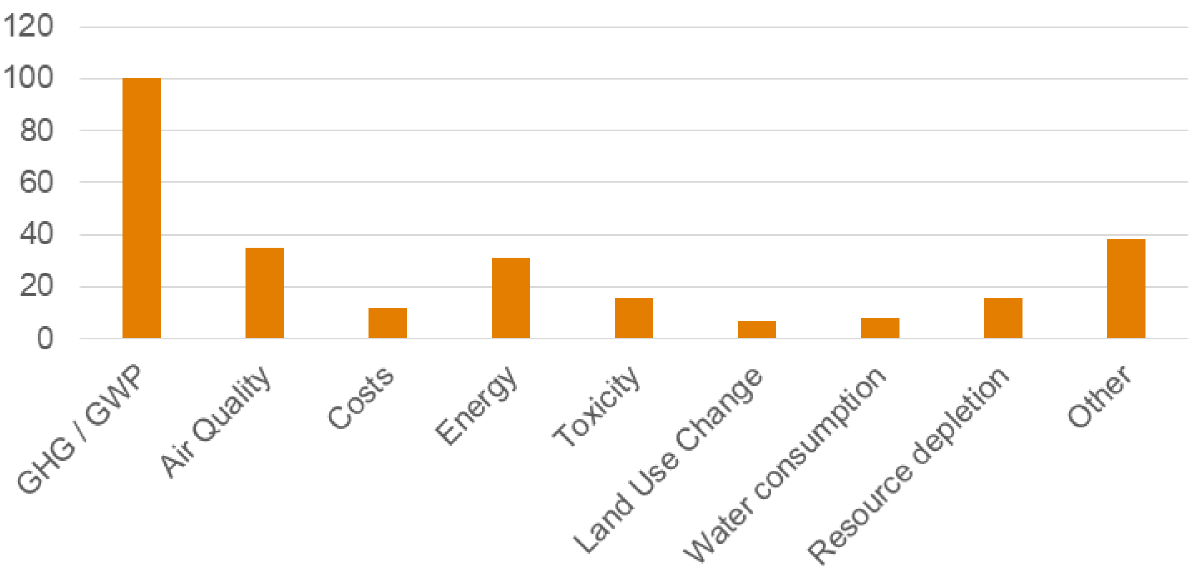
A1.1.3.1 Overview of literature reviewed

Literature pertaining to the life cycle impacts of fuel production is vast and has been jointly built by academic researchers, think tanks, standard setting bodies and government departments, among others. The aim of the literature review conducted was not to be exhaustive. The scope of the surveyed literature varied widely, with LCAs conducted on specific fuel chains/types of fuels, others delivered comparative assessments across fuels, and some others aimed at establishing methodological approaches to tackling several issues at once. The varying scopes of the assessed LCAs made reviewing them challenging.

A1.1.3.1.1 Impact Categories

Overwhelmingly, most of the reviewed studies focussed on GHG/GWP impacts (Figure A17). When 'Air Quality' is considered it often covers a number of distinct impact categories including smog (photochemical ozone) and particulates, but also pollutants linked to acidification and eutrophication.

Figure A17: Life cycle impact indicators addressed in the reviewed literature covering WTT fuel production studies

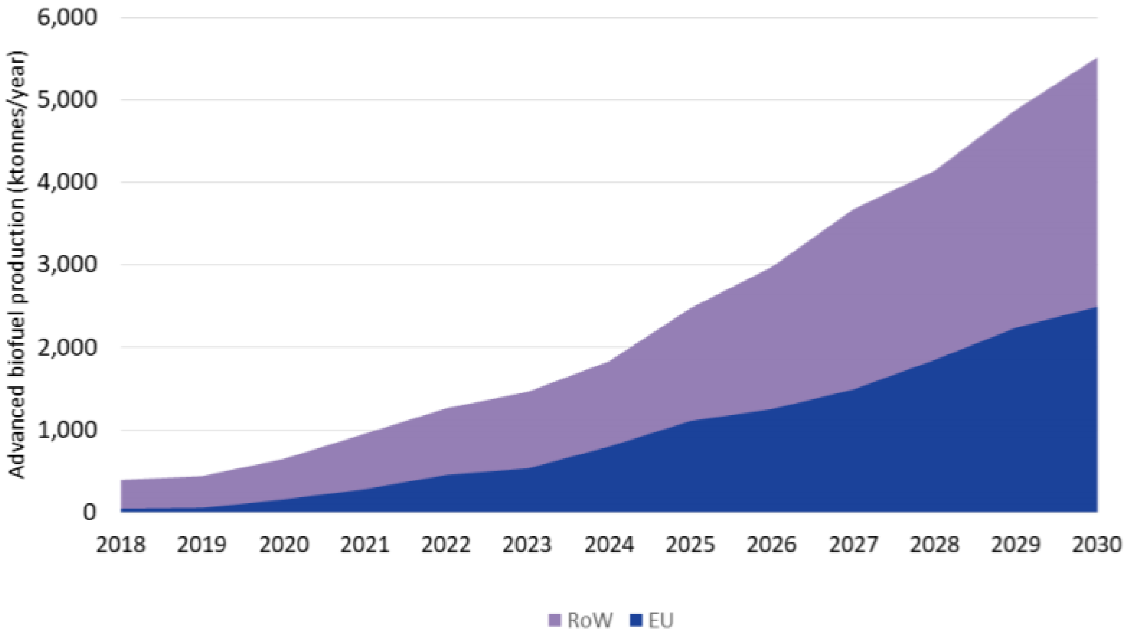


A1.1.3.1.2 Fuel types

While the current EU fuel mix is dominated by fossil fuels, literature reveals that a wide range of fuel types could make it into the European fuel mix in the future. For example, E4tech for the European

Commission (European Commission Joint Research Centre, 2019) investigated the potential ramp up of advanced biofuel production, illustrating the potential of covering part of the transport energy demand with novel fuels (Figure A18). The range of results between the different scenarios considered reflects the uncertainty in projecting these developments from the supply side.

Figure A18: Global advanced biofuel production potential under one scenario (excludes FAME, HVO, co-processing and alcohol catalysis) (European Commission Joint Research Centre, 2019)



Reviewed literature focuses strongly on biofuels and other novel fuel types. Because of the regulatory demands for GHG reporting, studies tended to focus on GHGs. Further, studies generally model the impacts of a single fuel chain, focussing on a particular feedstock, conversion technology and end-fuel. This increases the difficulty in making direct comparisons between studies, as different assumptions and data sources have been taken across studies.

A few large review studies of fossil fuels have been examined. These tend to be broader, because gasoline and diesel are widely and globally traded, so some of the key studies look at e.g. Europe gasoline mix as a whole.

The impacts from fuel production broadly result from two main areas – extraction/cultivation/collection of the feedstock and production of the fuel. The impacts from transport and storage steps are likely to be greater for crops compared to oils, as they have a comparatively lower energy density. Most reviewed studies did not include impacts from infrastructure.

The S2Biom and ISO methodologies recommend that emissions from capital goods be included. Further, the ILCD also recommends that emissions from capital goods are taken into account, unless it can be demonstrated that their contribution is below the cut-off criteria. Despite this, under the RED methodology (2009) emissions from the manufacture of machinery and equipment are not taken into account. This assumption was reflected in a number of reviewed studies, including (Jungmeier, et al., 2016), (Nie & Bi, 2018), and (Budsberg, et al., 2013). It is generally assumed that these impacts are small compared to the environmental impacts of feedstock extraction/cultivation/collection and fuel production. This assumption is nevertheless explored and investigated more closely in (Frischknecht, et al., 2007), where the contribution of the capital infrastructure across the LCA of several hundred products and services is examined. The authors conclude that capital goods must be included in the assessment of climate change impacts of non-fossil electricity, agricultural products and processes, transport services and waste management services, and in all LCAs which assess toxicity impacts. Assessment of the energy demand of transport services should include capital goods[35]. Given that

[35] However should be noted that their definition of 'capital goods' is wider than what we would think of as capital goods, so their assessment is not exactly comparable with our question here, which is should the emissions from the construction of biofuel production factories (and potentially agricultural equipment) be included?

biorefineries or biofuel production plants tend to have a smaller output compared to conventional oil refineries, the impacts associated with plant construction and capital goods may be higher on a per MJ of fuel produced basis. The impacts from infrastructure and capital goods could therefore be of particular importance to biofuels.

A1.1.3.2 General coverage of fuel chains in LCA

Multi-functionality (discussed in more detail in section A3.7) is an important issue in fuel LCA, and guidance on allocation of outputs largely follows the hierarchy provided in ISO 14040:

- First approach: subdivision of multifunctional processes
- Second approach: system expansion (including substitution), which allows addressing indirect impacts such as iLUC
- Third approach: allocation (used by JEC in WtW studies). Allocation should be performed in accordance with the underlying causal physical (incl. chemical and biological) relationship between different products or functions. When it is not possible to find a common physical causal relationship between the co-functions, ISO 14044 recommends performing the allocation according to another relationship between them. This may be an economic relationship or a relationship between some other (e.g. non-causal physical) properties of the co-functions, such as energy content, as often used in the allocation between different fuels co-produced in a refinery.

A1.1.3.3 Environmental impacts of fuels produced from primary fossil feedstocks

Box 2: Key messages: environmental impacts of fuels produced from primary fossil feedstocks

- In literature, GWP the most widely covered impact category, resource depletion and air quality categories
- Key stages of the lifecycle are: crude oil / natural gas extraction and processing
- Variability in emissions due to:
    - Origin of crude oil / natural gas (conventional vs non-conventional + location)
    - Levels of residual gas leakages, venting and flaring
    - Inclusion of combustion emissions in scope

A1.1.3.3.1 Introduction

In the context of this study, primary (non-waste) fossil fuels include most fuels produced from the processing of conventional and non-conventional crude oil and natural gas.

Crude oil, coal or natural gas extraction is known to require varying levels of energy, depending on the nature of the extraction site. Extraction also has potentially significant impacts on the environment, due to the techniques used (including offshore). Land-use change and consequences on local biodiversity, species or ecosystem services from mining operations are not necessarily addressed in LCAs. In addition, extraction requires significant amounts of water, which can be contaminated with hydrocarbons and other pollutants. Finally, extraction may come with the unintended release of unwanted gases, which are either vented or flared, thus potentially contributing to climate change and/or air pollution. Energy and water consumption, as well as the environmental and human toxicity impacts of pollutant release into water, air and soil, are generally captured in LCAs.

A1.1.3.3.2 Conventional crude oil and natural gas

Environmental hotspots in conventional crude oil and natural gas are mostly found at the extraction stage, where significant amounts of fossil energy are used to run the machinery and equipment required to extract crude oil (on and off-shore) and/or natural gas. Crude oil and natural gas extraction also require significant amounts of water, which is injected in wells to increase the amount of crude or gas extracted or recovered. Contaminated water then requires proper treatment before being rejected in the environment.

Crude refining and natural gas upgrading are performed in large scale industrial facilities, which also consume fossil energy, process water and chemicals. Gaseous oil refining effluents may be vented or flared into the atmosphere, thus adding to both global warming potential and local air pollution. The flaring of residual gases on its own accounts for more than 50% of oilfields GHG emissions (Exergia; COWI; E3M lab, 2015).

The following LCA impact categories (midpoints) are therefore particularly relevant to conventional crude and gas extraction and processing:

- Global warming potential (greenhouse gas emissions)
- Resource consumption (incl. non-renewable energy and mineral extraction)
- Water depletion
- Water and terrestrial eco-toxicity
- Water and terrestrial acidification
- Human toxicity
- Air quality (Photochemical ozone creation potential and summer smog)
- Ozone depletion

A1.1.3.3.3 Non-conventional crude oil and natural gas

Environmental impacts from non-conventional crude oil and natural gas extractions are expected to be more important due to the higher amounts of energy, water and chemicals used for extraction and on-site upgrading (e.g. cleaning of heavy tar sand oil into lighter crude oil). Following transport, refining and storage stages are not significantly different from conventional crude oil or natural gas processing.

A1.1.3.4 Environmental impacts of fuels produced from waste fossil feedstocks

Box 3: Key messages: environmental impacts of fuels produced from waste fossil feedstocks

- In literature, GWP is the most widely covered impact category
- Key stages of the lifecycle are: fuel production process, fuel combustion
- Variability in emissions due to:
    - Method of assigning emissions to waste fossil feedstocks
    - Range of different counterfactual uses of those feedstocks
    - Range of fuel production processes
    - Range of methods for accounting for emissions from fuel combustion

A1.1.3.4.1 Introduction and scope

This section is concerned with the identification of environmental hotspots in the process chains of fuels produced from waste fossil feedstocks. Most of the possible pathways are currently under development with technology readiness levels 5-8, processing waste fossil feedstocks which can be

- solid, e.g. waste plastics, rubber, the fossil portion of mixed waste streams[36],
- liquid, e.g. waste fossil oils
- gaseous, e.g. industrial gases containing CO or CO_2.

The feedstocks can be processed and converted to liquid fuels in a variety of ways. As elaborated in detail elsewhere (E4tech, 2018), generally, plastics and rubber tend to enter pyrolysis processes with further upgrading to diesel and gasoline. Mixed waste streams are most often gasified with the resulting syngas processed to diesel and gasoline via alcohol catalysis plus oligomerisation and refining or Fischer-Tropsch catalysis and hydrocracking. The syngas can also be upgraded via methanation to synthetic natural gas (SNG) or to hydrogen via water-gas-shift reaction. Given the low technology-

[36] These include municipal solid waste (MSW), refuse derived fuel (RDF) and commercial and industrial (C&I) waste

readiness of these routes, information is scarce and mostly confidential due to commercial reasons. The research in (E4tech, 2018) does not find active processing of liquid fossil wastes.

In the REDII, these fuels are referred to as ‘carbon recycling fuels’ (CRFs).

These fuels are currently only present in very small volumes in the European fuel mix, and there are a limited number of LCA studies in the literature covering waste-based fossil fuels. Most studies to-date have focussed on the GHG impacts of waste-based fossil fuels.

The key issue for waste-based fossil fuels is how emissions are assigned to the feedstock, given that it is a waste, and how the impacts from the fuel combustion are taken into account. Environmental impacts from fuel processing may also be substantial, but do not present key methodological challenges.

A1.1.3.4.2 Environmental impacts from waste fossil feedstocks

The major difficulty with assessing environmental burdens associated with waste fossil feedstocks (other than CO_2) is that in many cases the materials are in fact used in other ‘counterfactual’ energy recovery processes and might be diverted from these existing uses when processed into transport fuels. Therefore assigning them zero emissions at the point of collection, which is the approach currently adopted towards biogenic wastes and residues in the RED (European Union, 2009), risks underestimating the true environmental impact (E4tech, 2018). This point is further addressed in Section A1.2.3.2.

A1.1.3.4.3 Impacts from feedstocks – CO/CO_2

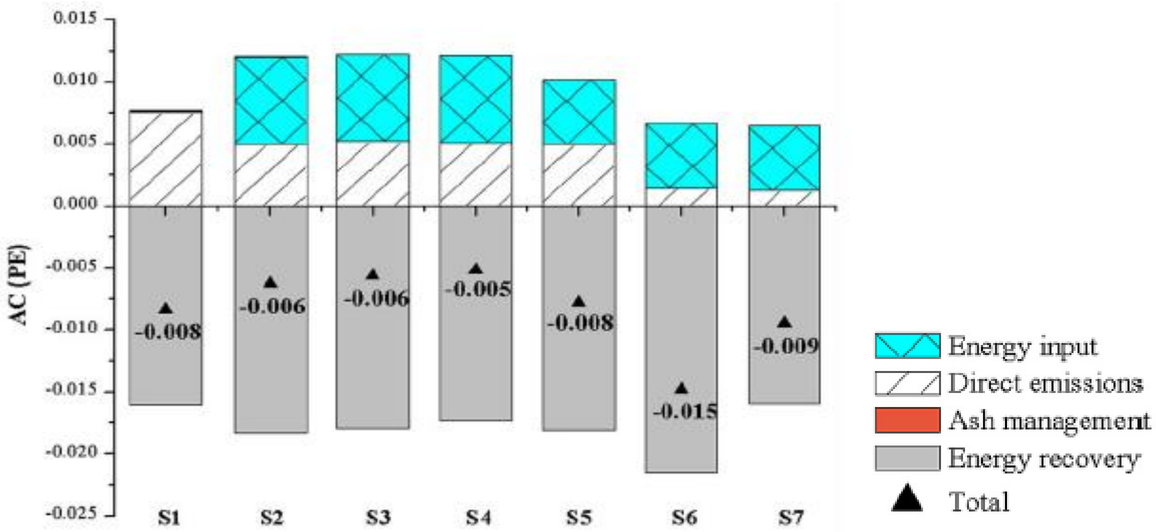
CO_2 as a feedstock does not contain any energy, and to produce a transport fuel all catalytic synthesis processes require hydrogen to react with the CO_2 and in microbial synthesis the microbes require H_2 to process the CO_2 into methane. The conversion of CO or CO_2 into fuels requires the use of specifically engineered and patented enzymes, microbes and catalysts, which, in turn, generate additional energy consumption and other environmental impacts.

A1.1.3.4.4 Impacts from processing

The availability and quality of LCA studies on waste to energy processing is currently limited, as a comprehensive review of 250 individual case-studies published in 136 peer-reviewed journal articles between 1995 and 2013 concluded (Astrup, Tonini, Turconi, & Boldrin, 2015). Most of these studies are reported to present impacts in the GWP and abiotic energy consumption.

One LCA of pyrolysis of non-recyclable plastics separated from MSW to produce diesel, (Benavides, Sun, Han, Dunn, & Wang, 2017) highlights process energy consumption as main driver of GHG emissions associated with the overall production process. Similarly, (Ou, Zhang, Zhang, & Zhang, 2013) show that the main contributor to GHG emissions associated with the production of ethanol from the fermentation of steel-mill waste gases is the electricity required in the process. (Dong, et al., 2018) provide insight into a wider range of impact categories (global warming, acidification, terrestrial eutrophication, photochemical ozone formation, human toxicity via air, as well as human & ecotoxicity via solid) and show that process energy significantly contributes to e.g. the acidification impact indicator (Figure A19).

Figure A19: Acidification potential in MSW-to-diesel chains



Source: (Dong, et al., 2018). *Notes*: S1 = MSW direct incineration, S2, S3, S4 = pyrolysis coupled with steam turbine, gas turbine/CC and internal combustion engine, respectively; S5, S6, S7 = gasification pyrolysis coupled with steam turbine, gas turbine/CC and internal combustion engine, respectively

Besides the process electricity consumption, the main drivers of eco/human toxicity impact indicators of waste gasification and pyrolysis processes are the disposal of ash/slag/other residues (Zaman, 2013), (Dong, et al., 2018) as well as the potential use of by-products such as e.g. char from plastics pyrolysis as a replacement for pet coke (Benavides, Sun, Han, Dunn, & Wang, 2017).

A1.1.3.5 Environmental impacts of fuels produced from crop/forestry-based feedstocks

Box 4: Key messages: environmental impacts of fuels produced from crop/forestry-based feedstocks

- In literature, GWP is the most widely covered impact category
- Key stages of the lifecycle are: crop cultivation, land use change, fuel production, fuel combustion
- Variability in emissions due to:
    - Range of cultivation practices
    - Range of environmental impacts which might result from a given cultivation practice
    - Wide of land use change emissions, and uncertainty in method for assessing indirect land use change
    - Range of fuel production processes

A1.1.3.5.1 Introduction and scope

In this section, the environmental hotspots associated with fuels produced from biomass which is cultivated specifically for the purpose of fuel production are explored. This includes crops such as maize, sugar cane and rape seed oil, and forests or plantations cultivated specifically for biofuel production. Depending on the production process, a wide range of fuels can be produced from crops or cultivated forests, including ethanol, methanol, FAME, HVO and Fischer-Tropsch diesel (Figure A20). There are particular environmental impacts associated with agriculture and forestry which are distinct from those caused by fossil fuel extraction, therefore fuels produced from these processes are considered separately within this section.

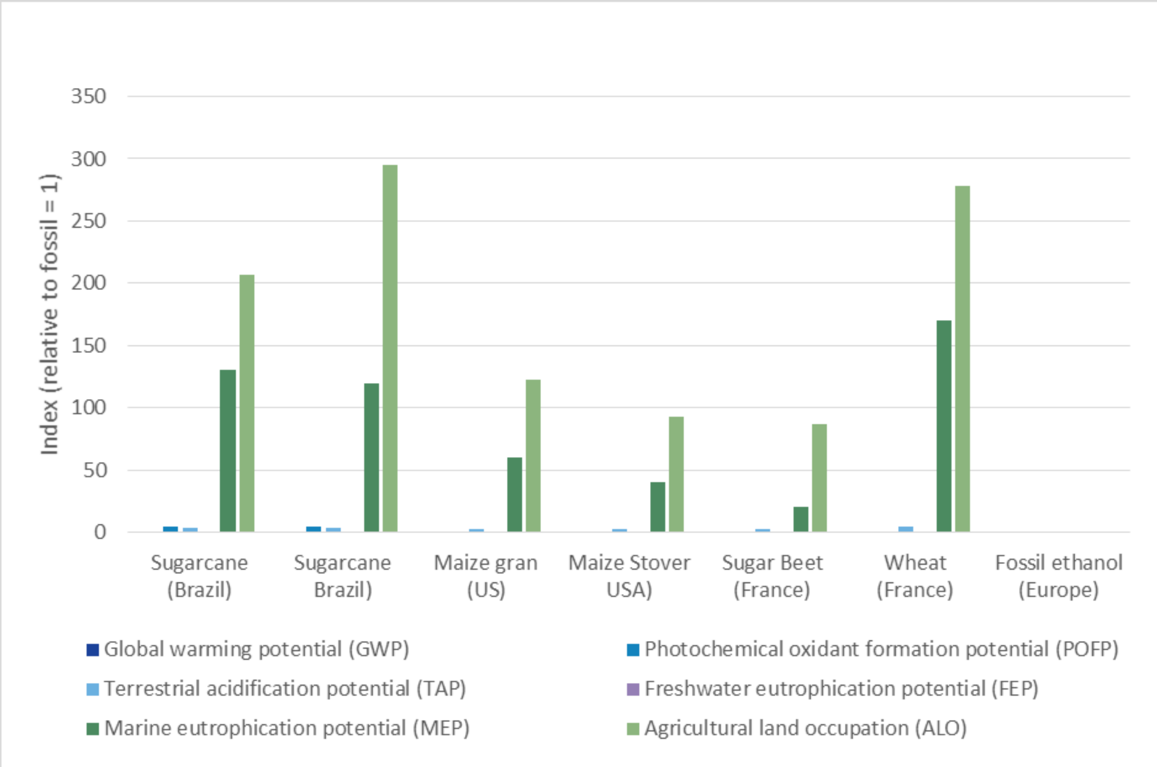
The key lifecycle stages which contribute substantially to the overall environmental impacts of crop/forestry-based biofuels are: land use change, cultivation, and fuel production. Differences in these aspects of the lifecycle account for much of the variability in impacts between different fuel types, and they are discussed in more detail in the following sections. Combustion emissions are often assumed to be zero, an assumption which is discussed and challenged in section A1.1.3.5.5.

A1.1.3.5.2 Which impact categories have been included in LCA studies of fuels produced from crop / forestry –based feedstocks?

The majority of LCA studies of fuels consider GHG emissions, and many do not consider any other impact categories. This is likely partly due to legislation, such as the Renewable Energy Directive in the EU and the Renewable Fuel Standard in the USA, which require the assessment of alternative fuels based on only their GHG emissions.

Nevertheless, other impact categories are particularly important when considering agricultural systems, due to the close relationship between the technosphere and ecosphere in agricultural LCAs, as chemicals are potentially put directly into the environment. Muñoz et al (2013) for example compare a number of bioethanol fuels with fossil ethanol, finding that for all of the different crops considered, the GHG emissions of the bioethanol are always lower than the fossil ethanol. However, marine eutrophication, agricultural land occupation and terrestrial acidification are higher for all crops (Figure A20). Interestingly in this study freshwater eutrophication, which is often quoted as a high risk from agriculture, is lower for all bioethanol fuels considered than for fossil ethanol. The Agri-footprint database was developed specifically for agricultural LCAs and contains some elements not offered by other LCA databases (Agri-footprint, 2018).

Figure A20: Comparison of environmental impacts between biogenic and fossil ethanol production



Sources: E4tech and (Munoz, et al., 2013)

In addition to these typical LCA mid-point impact categories, some studies consider other metrics of comparison such as water footprint and nitrogen footprint (Pelletier, 2014). These do not formally follow LCA methodology because they don't convert this footprint into an 'indicator', but they can nevertheless be useful tools for comparison between agricultural systems.

A1.1.3.5.3 Cultivation

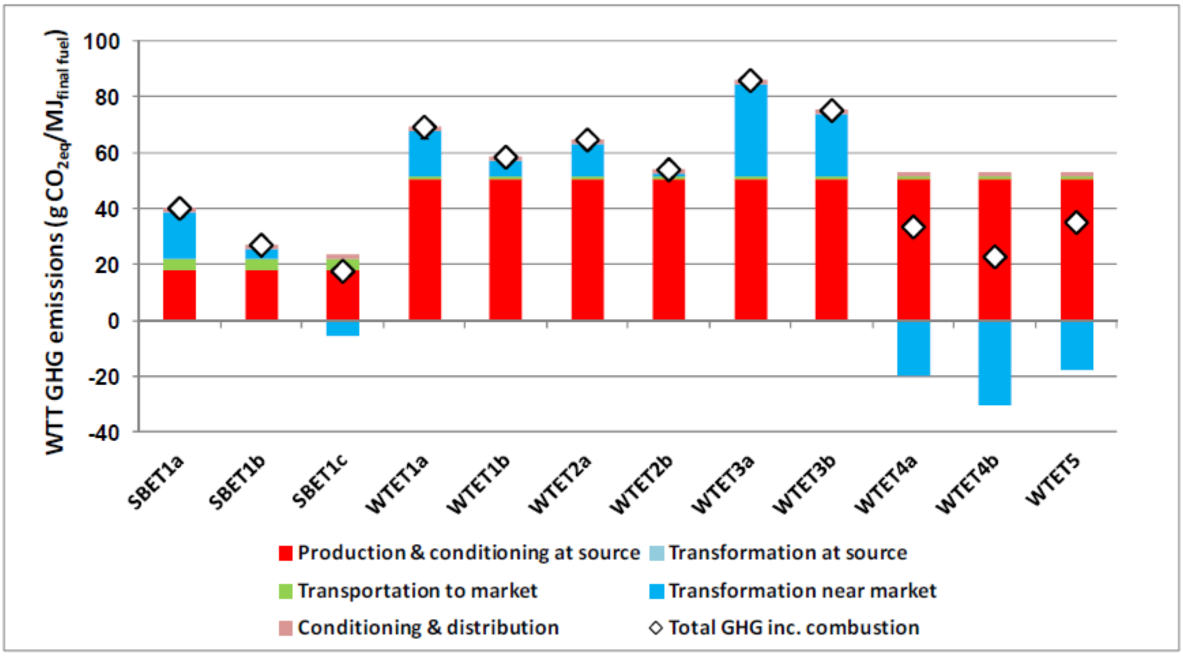
The use of agricultural inputs such as fertilisers and pesticides can cause significant environmental impacts, due to both their production and use. For example, substantial GHG impact can result from the release of N_2O from soils after fertiliser application, due to the high GWP of N_2O (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b). There are also a range of other non-GHG environmental impacts caused by the application of chemicals. One study (M.H. Rocha, 2014) for example, which reviewed LCA studies of biofuels in Brazil, notes a substantial contribution from the production and use of fertiliser and chemicals (herbicides and pesticides) to acidification potential, eutrophication potential and human toxicity potential.

The inputs required for crop cultivation can vary depending on many factors, including what crop is being cultivated, different soil type on which cultivation takes place, conventional farming practices in that region, prevalence of pests etc. Moreover, the environmental impact associated with the use of agricultural inputs directly on the field can vary substantially depending on the conditions in which the fertilisers are applied. Consequentially there is large variation in the environmental impacts from crop cultivation reported in the literature. For example, soil N_2O emissions from individual fields can vary by at least three orders of magnitude, depending on local conditions such as soil type, climate, fertiliser rate etc (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b).

This is also illustrated in Figure A21, where the large difference in the 'production' GHG emissions between sugar beet and wheat is largely due to the fact that wheat production requires more nitrogen than sugar beet, resulting in higher field emissions.

Therefore, unless an LCA study is specific to the particular farm, year of cultivation etc. then soil N_2O emissions from the cultivation of a particular crop can vary substantially. Average results for a crop or region are generally calculated using models or assumed values, which means that any 'average' value has large error bars inherent.

Figure A21: WTT GHG emissions for sugar beet (SBET labels) and wheat (WTET labels) pathways



Source: (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b)

There is also high uncertainty in assessing emissions from the application of agricultural inputs, and the methodology chosen, and type of data used can give a wide variety of results. The JRC note that the uncertainty in estimates of GHG emissions from soils dominates the errors in the final GHG balance of some biofuels (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b).

A1.1.3.5.4 Land use and land use change

The use of land for the cultivation of crops, and the conversion of land from an alternative use to crop production, can have substantial environmental impacts. The conversion of land into agricultural land (land use change) can either happen in the location where the crops are being grown, in which case it is called direct land use change, or it can happen in another location because existing cropland is used to grow crops for fuels and other land must be converted into cropland to supply the demand for food (indirect land use change) after subtracting other elasticities of the global market (such as improved avoidance of losses, increased productivity on existing land, increased feed use efficiency, etc).

The environmental impacts from land use change can be substantial, as illustrated in a recent study by E4tech, Ecofys and IIASA which considers the GHG emissions from both direct and indirect land use change using a global agricultural and forestry equilibrium model (GLOBIOM) (Valin, et al., 2015). Given that the GHG emissions from fossil diesel or gasoline in the EU are around 90 gCO_2e/MJ (European Union, 2009), there is a risk that for some biofuels they could have worse GHG emissions than fossil fuels when land use change is included. See also Section A1.2.3.3.

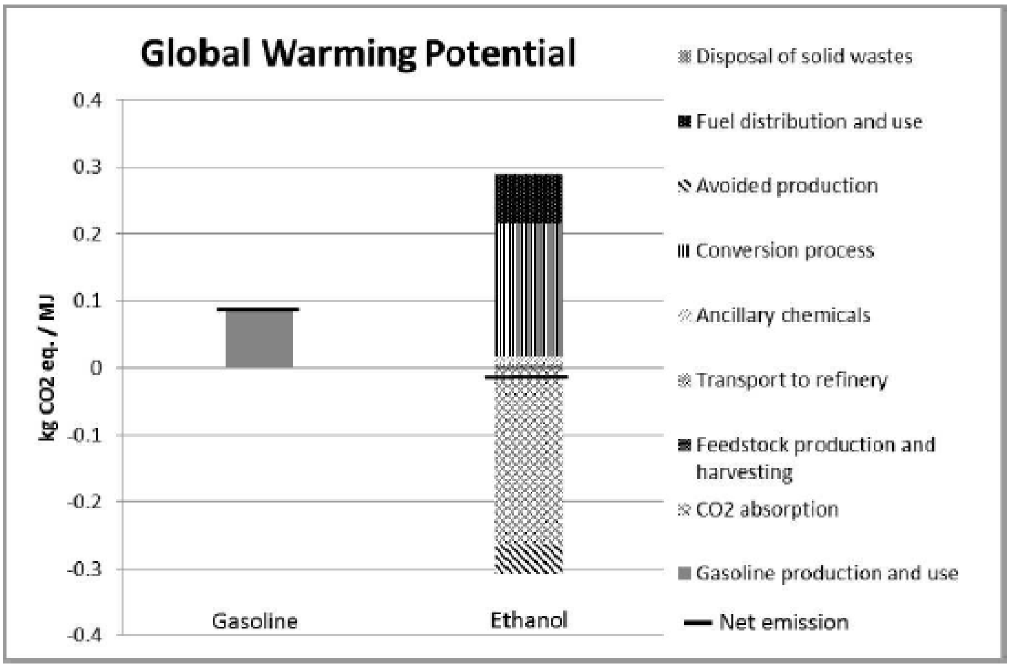
A1.1.3.5.5 Fuel combustion

The point emissions from fuel combustion in an engine are the same, for a given fuel type, regardless of whether that fuel is produced from biological or fossil feedstocks. Nevertheless, assigning environmental impacts to emissions from biofuel combustion, is dependent on how biogenic carbon is treated in the LCA methodology.

In the production of biofuels, biogenic carbon is taken up by living biomass, converted into a fuel including some release of carbon during the process, and then released when that fuel is combusted in the engine.

Generally, this results in a large negative carbon flow whilst the crop is growing, and a large positive carbon flow (release of CO_2) from combustion of the fuel and release of CO_2 during the production process (for example, see Figure A22).

Figure A22: Global warming potential of ethanol produced from willow including credit for CO_2 absorbed during cultivation and release of CO_2 during conversion process and fuel use.



Source: (Budsberg, et al., 2013)

A1.1.3.6 Environmental impacts of fuels produced from waste/residue biogenic feedstocks

Box 5: key messages: environmental impacts of fuels produced from waste /residue biogenic feedstocks

- In literature, GWP is the most widely covered impact category
- Key stages of the lifecycle are: fuel production process, fuel combustion
- Variability in emissions due to:
  - Method of assigning emissions to waste biogenic feedstocks
  - Range of environmental impacts from diverting feedstock from existing use
  - Range of fuel production processes

Due to sustainability concerns about biofuels made from crops, fuels made from wastes and residues are becoming increasingly prevalent. FAME and HVO made from waste fats and oils are already widely produced in the EU. Ligno-cellulosic ethanol is also produced from agricultural residues such as straw and corn stover in a number of commercial-scale plants worldwide. However, several other technologies for the production of transport fuels from wastes and residues are still at demonstration scale (IRENA, 2016).

The methodological approach to assigning emissions to the biogenic wastes and residues used for fuel production differentiates this category of fuels from the crop-based biofuels discussed in section A1.1.3.5.

As for biofuels from crops / harvested forestry, the fuel production process can make a substantial contribution to the overall environmental impacts of the fuel. As some of the processes for biofuel production from wastes and residues are still at early stage of technological development, obtaining accurate data on fuel production processes may be challenging. In addition, in some cases there is not a dominant process design, so it is important to be transparent around the technological specificity of the study and whether it refers to one particular type of (for example) pyrolysis technology, or whether it attempts to represent an average of all pyrolysis processes which are being developed today.

Because of the low sugars content and high lignin content in some wastes and residues, and also the risk of contamination, the processing step may be more energy-intensive than for crop-based biofuels. This can increase the environmental impact of the process, but could also be offset by the use of additional waste biomass to provide energy to the process, e.g. using an on-site CHP fuelled by waste biomass.

Additional methodological aspects are covered in Section A1.2.3.4.

A1.1.3.7 Environmental impacts of e-fuels

Box 6: key messages: environmental impacts of e-fuels

In literature, GWP and acidification potential are the most widely covered impact categories

- Key stages of the lifecycle are: electricity production
- Variability in emissions due to:
  - Source of power for hydrogen production (fossil, nuclear, renewable)
- Source of CO_2 and allocation of emissions to CO_2

A1.1.3.7.1 Introduction and scope

In this study, the term ‘e-fuel’ is used to refer to fuels for which the energy source is derived solely from power. This encompasses hydrogen produced from electricity, and fuels which are made by subsequent reaction of that hydrogen with CO_2. Fuels which are produced from waste energy-containing gases such as CO are treated as secondary fossil fuels.

Global hydrogen production is currently primarily based on fossil sources (49% from natural gas, 29% as co-product from liquid hydrocarbon refining and 18% from coal) (Lozanovski & Schuller, 2011). Only 4% of current H_2 production comes from electrolysers, which, in turn, use a mix of fossil and renewable electricity, based on the grid composition in producing countries. Therefore, the share of renewable H_2 remains fairly limited. In addition to the use of renewable electricity in electrolysers, renewable hydrogen may also be produced through biomass gasification and steam reforming applied to bio-methane. Although these production modes are marginally utilised today, related LCA considerations are important for future use, since renewable hydrogen production is expected to increase in the near future.

A1.1.3.7.2 Electrolysis

All of the e-fuel chains considered in this study begin with the production of hydrogen in an electrolyser. Syngas could also be produced via electrolysis if co-electrolysis of water and CO_2 is use, however this is not explicitly considered in this study.

Environmental impacts from the production of hydrogen from electricity are primarily due to the source of electricity used to run the electrolyser. When renewable power is used, the impacts from manufacturing and end-of-life of the renewable generation asset can become significant. Another important methodological consideration is the amount of water used in the electrolyser, along with the energy needed to treat it before it enters the electrolyser.

A1.1.3.7.3 Fuel production

For the production of carbon-containing fuels such as methane, hydrocarbons or methanol; hydrogen must be further reacted with CO_2.

CO_2 can either be captured from existing point-sources of fossil or biogenic CO_2, or from the atmosphere, where it is known as Direct Air Capture (DAC). There is substantial variation in the energy required for CO_2 capture even from point source, across the literature. For example (Voldsund, 2019) illustrate the range of CO_2 emissions which can result just for CO_2 capture from a cement plant, depending on the type and operation of the capture technology. (Fasihi, 2019) illustrate a substantial range in the energy demand from different DAC processes.

There is also a methodology point which must be considered in the LCA of e-fuels: whether the additional emissions from the capture of CO_2 from point sources is assigned 100% to the e-fuel, or whether these additional emissions are averaged over the CO_2 and the primary product of the CO_2 producing process.

A1.1.4 Electricity cycle only

This section aims at the identification of the key lifecycle environmental impacts of electricity generation. In general, most LCA with the production of electricity as the (main) focus comprise the following lifecycle sub-stages: Infrastructure provision, fuel production and plant operation including maintenance. As electricity generation deploys a wide range of – in part – fundamentally different technologies, their respective impacts vary greatly both in terms of quality and quantity, depending on the electricity split.[37] Furthermore, the different generation technologies differ in respect to their contributing life cycle phases. For instance, coal powered plants over the course of their technical lifespan will produce most GHG (and other) emissions in the 'use-phase' of their life cycle, while emissions arising from upstream processes will be negligible in comparison. In contrast, electricity from photovoltaics is virtually emission-free during generation with most emissions related to upstream processes for infrastructure like mining and processing of utilised materials.

A1.1.4.1 How are different environmental impacts of electricity generation covered by literature?

As stated above, a broad spectrum of different technologies is utilized for electricity generation which leads to corresponding different impacts. While most studies focus on the GHG intensity (and to a lesser extent on the primary energy demand per energy supplied, e.g. (Kleinertz, Dr. Pellinger, Dr. von Roon, & Hübner, 2018)) of electricity chains, some cover additional categories or comprise/aggregate further categories within a single indicator (e.g. the ecological scarcity method utilized by GaBi). Few studies approach the assessment of impacts in a more holistic way ((Turconi, Boldrin, & Astrup, 2013), (Helms, et al., 2014), (PSI/EMPA/ETHZ, 2016) (Thelma Project), (Razdan & Garrett, 2015), (Frischknecht, et al., 2014)) but they all differ in terms of applied impact assessment. The following Table A1: provides an overview over the analysed impact categories of electricity generation in current LCA:

Table A1: Covered impact categories in electricity generation LCA literature

Environmental impact categories	Abbrev.	Helms et al. (2014)	Turconi et al. (2013)	THELMA Project (2016)	Hertwich et al. (2014)	Razdan & Garrett (WP only) (2015)	Frischknecht et al. (PV only) (2014)
Global Warming Potential	GWP	✓	✓	✓	✓	✓	✓

[37] http://www.iinas.org/tl_files/iinas/downloads/GEMIS/2015_PEF_EU-28_Electricity_2010-2013.pdf

Environmental impact categories	Abbrev.	Helms et al. (2014)	Turconi et al. (2013)	THELMA Project (2016)	Hertwich et al. (2014)	Razdan & Garrett (WP only) (2015)	Frischknecht et al. (PV only) (2014)
Acidification Potential	TAP	✓	✓	✓	✓	✓	✓
Eutrophication Potential	EP	✓	✓	✓	✓	✓	–
Photochemical Ozone Creation Potential	POCP	✓	–	✓	✓	✓	✓
Abiotic Resource Depletion Potential	ADP	–	–	✓	✓ [5]	✓	–
Energy consumption		✓ [1]	–	✓	✓	✓	✓
(Indirect) Land Use	ILUC	–	–	✓ [4]	✓	–	✓
Human Toxicity Potential	HTP	✓ [2]	–	✓ [3]	✓	✓	✓ [3]
Eco-toxicity	ETP	–	–	✓	✓	✓	–

Notes: 1) CED: cumulative energy demand; 2) addressed via particulate matter, PM10; 3) including PM10; 4) natural land transformation; 5) metal depletion.

Although only a fraction of the existing studies could be analysed, the findings are in line with most contemporary LCA. As concerns the covered environmental impacts, most comprise the following categories:

- Global Warming Potential,
- Acidification Potential,
- Eutrophication Potential,
- Photochemical Ozone Creation Potential,
- Energy Consumption, and
- Human Toxicity Potential.

A1.1.4.2 What are the main environmental impacts of electricity generation chains?

As mentioned above, the differences in technology lead to vastly different results for environmental impacts and contributing life cycle stages. Consequently, a detailed analysis of the main technologies is required. Generally, electricity chains consist of the following sections:

- Upstream processes, including:
  - Raw material extraction, refining and processing
  - Manufacturing of plant components and auxiliaries
  - Transport processes
- Plant construction:
  - Transport processes
  - Installation
- Power plant operation:
  - Fuel provision[38]

[38] For thermal / nuclear power plants only.

- Incineration
- Maintenance

- End-of-life:
  - Dismantling
  - Recycling of components
  - Disposal of wastes
  - Transport processes

In their comprehensive system analysis, (Turconi, Boldrin, & Astrup, 2013) investigated 167 studies in terms of their GWP, acidification potential and eutrophication potential. They found that for the three mentioned impact categories that there are significant differences between renewable energy sources (RES) on the one hand and fossil-fuelled power generation on the other, both in terms of order of magnitude of results and in terms of decisive life cycle stage.

a) GWP

Per MWh of electricity, fossil-fuelled power plants emit GHG in a range from 380 kg CO_2-e (natural gas) up to 1300 kg CO_2-e (lignite), whereas RES GHG emissions lead to significantly lower impacts, varying from 2 kg CO_2-e per MWh (hydro) to 190 kg CO_2-e / MWh (photovoltaics). Nuclear power too showed comparatively low GHG emissions, ranging from 3 – 35 kg CO_2-e / MWh. Regarding the contributing life cycle stages, for all fossil-fuelled sources, the section power plant operation with its direct incineration emissions makes by far the highest contribution to total emissions. Provision of the energy carrier also contributed to GHG emissions, especially for natural gas and hard coal but to a far lesser extent than direct emissions. For all investigated fossil-fuelled plants, infrastructure was found to be negligible. Between RES and nuclear power, infrastructure provision showed the highest contribution for wind power, hydro power and photovoltaics, while fuel provision and power plant operations where responsible for the majority of emissions for biomass and nuclear power.

b) Acidification potential

Similar to GWP emissions for fossil-fuelled power plants the acidification potential is several magnitudes of order higher, compared to RES and especially nuclear energy. However, (Turconi, Boldrin, & Astrup, 2013) found huge spreads within the group of fossil fuels, ranging from 0.01 kg SO_2 / MWh (natural gas) up to 8 kg SO_2 / MWh (oil). Again, the operation of power plants proved to be decisive for fossil fuels. In contrast, SO_2 emissions ranged from 0,001 kg / MWh (hydro) up to 0.94 kg / MWh (biomass), with power plant operations and fuel provision contributing most for biomass and infrastructure for PV and wind power. Nuclear power and hydro power showed very little SO_2 emissions throughout their respective life cycles.

c) Eutrophication potential

Also, for acidification there is a general difference in order of magnitudes between fossil generation and renewable since also eutrophication is strongly influenced by NOx emissions Whereas emissions from fossil fuels range from 0.2 kg NO_x / MWh (lignite, natural gas) up to 3,9 kg NO_x / MWh (hard coal), RES respectively nuclear power plants emit NO_x from 0,004 kg / MWh (hydro) up to 1,7 kg / MWh (biomass). Again, plant operations and fuel provision largely contributed to total NO_x emissions for the fossil-fuelled plants as well as biomass, while infrastructure was key with respect to photovoltaics. Electricity generation from hydro, wind and nuclear power plants emitted comparatively few NO_x.

(Garcia, Marques, & Freire, 2014) showed similar results that are in line with the findings from (Turconi, Boldrin, & Astrup, 2013) However, neither nuclear energy nor electricity from biomass were covered.

(Garcia, Marques, & Freire, 2014) carried out a LCA on electricity generation in Portugal. Regarding the impact categories covered under a) – c), Martins et al. discovered similar trends – fossil-fuelled electricity resulting in significantly larger impacts throughout all technologies under study. Here, too, the differences between conventional power generation and RES amounted to several magnitudes, with the exception of electricity of biogenic origin (e.g. bio-gas, bio-methane) and waste incineration with results between the aforementioned. However, as (Garcia, Marques, & Freire, 2014) did not disaggregate their results regarding life cycle stages, the observation of importance of contributing life cycle stage cannot be confirmed.

d) Photochemical Ozone Creation Potential

Regarding POCP, (Garcia, Marques, & Freire, 2014) discovered a similar trend observed in the impact categories mentioned above. Fossil-fuelled power generation leads to partially significantly higher results. Especially electricity from fuel oil burning (748 mg C_2H_4 – eq. / kWh_{el}) represents an extreme outlier, with other fossil-fuels ranging from 27 – 291 mg C_2H_4 – eq. / kWh_{el} (natural gas and coal power). Electricity from RES resulted in considerably lower impacts on average, ranging from 1 – 68 mg C_2H_4 – eq. / kWh_{el} (hydro and biogas, respectively). In contrast to the above, RES did not achieve advantageous results unanimously. Electricity from biogas, for example leads to higher emissions, compared to electricity from natural gas[39].

e) Energy consumption

In terms of energy consumption, expressed as the cumulative non-renewable fossil energy demand (nREn), Martins et al. found results analogous to the impact category GWP, with results from fossil fuels being significantly higher across all investigated technologies, ranging from 6,47 $MJ_{prim.\ fossil}$ / kWh– 13,16 $MJ_{prim.\ fossil}$ / kWh (natural gas and fuel oil). On the other hand, RES, especially hydro and wind power achieved results as little as 0,04 $MJ_{prim.\ fossil}$ / kWh with biogas and waste incineration remaining between the extremes (1,31 $MJ_{prim.\ fossil}$ / kWh and 1,71 $MJ_{prim.\ fossil}$ / kWh, respectively).

The following Table 2.4 comprises the results from (Turconi, Boldrin, & Astrup, 2013) and (Garcia, Marques, & Freire, 2014). Further illustrative information is also provided in Figure A23 from (ANL, 2012).

Table A2: Qualitative comparison of impacts from different lifecycle stages by electricity generation type for different environmental impact categories

Type	Lifecycle stage	GWP	AP	EUT	POCP	ADP
Coal	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	-	-	-	-	-
	Plant operation	++	+	++	+	++
	Infrastructure/upstream	--	--	--	--	--
Fuel Oil	Fuel provision	-	-	-	-	-
	Plant operation	++	++	+	++	++
Natural Gas	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	-	-	-	-	-
	Plant operation	+	Ø	-	Ø	+
Biomass[1]	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	+	+	+	-	-
	Plant operation	Ø	Ø	Ø	Ø	-
Biogas[2]	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	+	-	-	-	-
	Plant operation	+	Ø	-	Ø	-
PV	Infrastructure/upstream	-	-	-	-	-
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--
Wind	Infrastructure/upstream	-	-	-	-	-

[39] There is no simple answer as to why this is the case: it could be due to the choice of the method which allows for some materials to result in negative impacts. When assessing with ReCiPe without negative impacts, for example, the results are reversed. Moreover, as POCP doesn't constitute a 'linear' relation between emissions and impacts, it is always subject to the underlying model.

Type	Lifecycle stage	GWP	AP	EUT	POCP	ADP
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--
Hydro	Infrastructure/upstream	--	--	--	--	--
	Fuel provision	--	--	--	--	--
	Plant operation	--	--	--	--	--

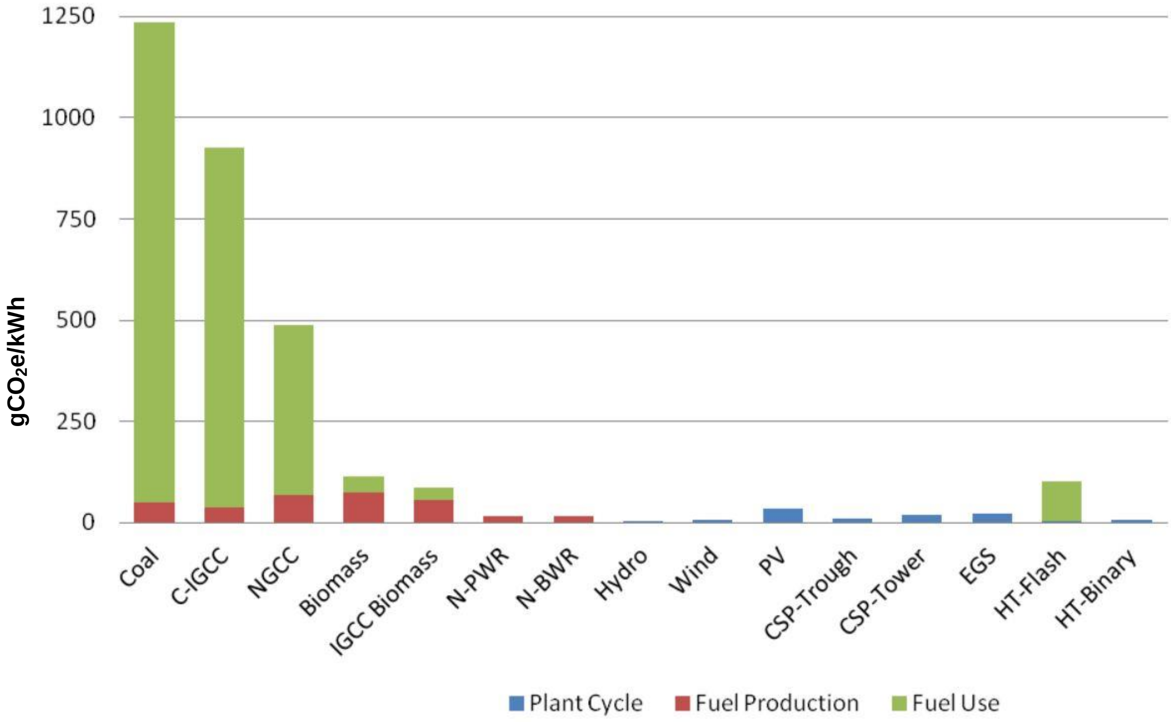
Notes:

++ = very high impact, + = high impact; - = low impact; -- = very low impact; Ø = average;

Excluding waste biomass. Exact values dependent on the type of biomass, e.g. wooden biomass carries other burdens than crops.

(2) See above

Figure A23:Plant construction and operation GHG emissions of different power systems (gCO_2e/kWh)



Notes: C-IGCC: Coal – Integrated Gasification Combined Cycle; NGCC: Natural Gas Combined Cycle; N-PWR: Nuclear – Pressurized Water Reactor; N-BWR: Nuclear – Boiling Water Reactor; PV: Photovoltaic; CSP: Concentrated Solar Power; EGS: Enhanced Geothermal System; HT-Flash: Hydrothermal (Geothermal) power plant with Flash-Steam configuration; HT-Binary: Hydrothermal power plant with binary cycle configuration;

Source: (ANL, 2012)

A1.1.4.3 How do transmission and distribution (T&D) of electricity influence the results?

Even though grid feed-in and distribution of electricity can be assumed to be equal throughout all technologies[40], their characteristics, especially transmission and distribution losses play a significant role for the system as a whole. This is also important in respect to a system comparison of electricity with other energy sources or when comparing different countries with different T&D networks or scale. (Garcia, Marques, & Freire, 2014) found that transmission and distribution impacted results across all

[40] An exception could be made for offshore wind power since grid integration requires specifically long cable connections to account for the distance to the main land (for reference, see Hertwich et al.)

investigated impact categories, with the transmission grid accounting for higher impacts with respect to the impact categories GWP, non-renewable fossil energy demand and abiotic depletion. The distribution grid accounted for higher impacts with respect to the impact categories acidification potential, POCP and eutrophication. While in total, (Garcia, Marques, & Freire, 2014) found that impacts due to infrastructure provision for both T&D grids where comparatively low or even negligible[41] (< 5 %), network losses, amounting to 5 % – 9 % of total environmental impacts where in fact significant (Garcia, Marques, & Freire, 2014) . As the T&D grid with its specifications is a country-specific metric, results may vary accordingly and thus should be subject to further investigations. Furthermore, the level of voltage is of crucial importance regarding grid losses, i.e. the lower the voltage the higher the losses. This should be considered when assessing different types of charging infrastructure, for example.

Moreover, in view of country-specific generation profiles, environmental impacts will differ accordingly (Itten, Frischknecht, & Stucki, 2012): They found that GHG-emissions per kWh of electricity generation in Europe range widely, reflecting the differences in a predominantly renewable generation mix versus a coal-heavy power production. Similar variations in the carbon intensity of electricity within Europe are illustrated in Figure A16 above.

In addition, because electricity is subject to external trade as a commodity from one country to another or several others, this has an influence on the environmental impacts (e.g. carbon intensity) when investigating the national consumption mix (the electricity that is consumed in a country) but not on the production mix (the electricity that is produced within a country). For a region like the EU28, these effects cancel each other out, but matter when comparing the consumption mix of a country or on a smaller scale in general.

Generally, it can be stated that contribution to different impact categories as well as the decisive life cycle phase are a function of the deployed generation mix and its' specifications (e.g. RES vs. conventional, age, state of the art, etc.). It can also be concluded that , while most studies focus on the impact category climate change (often referred to as Global Warming Potential with a time frame of 100 years, GWP 100) as traditionally the most important criteria (for reference, see (Wiedmann, et al., 2011), other impacts of electricity generation cannot be understated in order to achieve a comprehensive and integrated overview.

A1.2 Summary of the identified methodological options from the literature for vehicle LCA

A1.2.1 Vehicle specification and operation

This section provides a discussion of the methodological approaches for defining key input data / assumptions, with a particular focus on the level of simplification/aggregation or detail found in LCA analyses. Later section will cover specific aspects of vehicle production and disposal.

The following Table A3 provides a summary of the various approaches for defining and setting assumptions for key vehicle characteristics and performance criteria that are relevant to the specification (also impacting on the vehicle cycle considerations) and operational phase impacts for the full lifecycle. The table includes a mix of key parameters and approaches identified in the detailed review of key external literature, as well as Ricardo's other work and internal knowledge / expertise, ordered by increasing complexity for each parameter set.

The table also provides a summary assessment of the relative importance / influence of the parameter on the LCA outcome and an indication on which approaches were adopted by the studies we reviewed in detail. The assessment of the findings were used to inform our preliminary proposals on prioritisation for this project, which were subsequently presented and discussed with stakeholders in the Delphi Survey and expert workshop (see Appendix A2).

Broadly speaking the types of approaches can be broadly categorised into the following types:

d) ***Simple / high-level characterisation:*** Those using high-level data or assumptions based on typical examples of representative vehicles, or values taken from the literature / public domain;

[41] Only for electricity from hydro power with inherent low emissions are emissions from T&D infrastructure provision significant in relation. This is however limited to the impact categories acidification potential and eutrophication potential.

e) ***Intermediate approaches:*** Based on more detailed, but simplified methodologies / calculations to better account for variations in key parameters between vehicles or powertrains, or more closely define operational usage.

f) ***Complex characterisation:*** Those based on more complex methods, such as vehicle tear-downs and complex simulation approaches.

The approach adopted by different studies unsurprisingly varies in relation to their scope and resources: those studies that have a narrower focus (e.g. on a subset of specific vehicle types) are more likely to be able to adopt more complex analyses, whilst most of the broader comparative analysis studies tend to adopt more generic approaches in most cases. However, some larger studies, such as (PSI/EMPA/ETHZ, 2016), have adopted more complex simulation approaches for different vehicle types, though this study did not cover both light and heavy-duty vehicles, nor simultaneously explore different energy chains in detail.

In general, spatial/regional variations are not accounted for in most LCA studies, except for those with a specific objective to explore them, usually to inform policy analysis. In such cases, relatively simple assumptions are generally made to account for such variability, with appropriate sensitivity analysis for key parameters due to their inherent variability (e.g. different grid electricity mixes, or lifetime mileage assumptions) or uncertainty (e.g. number of battery replacements for future electric vehicles).

Table A3: Summary and assessment of the key options and methodological approaches identified for defining vehicle specification and operational performance

Element	Impact	Options			
		#	Type	Description	Studies
Activity (km)	High	1	Lifetime/average annual	Only considers total lifetime activity, assumes average annual mileage and average vehicle life. May include split by urban/rural driving	**8**
		2	Age-dependant annual	Accounts for higher mileage profile for newer vehicles, declining over time (e.g. via weighting factor)	**1**
		3	N/A	Not defined or not applicable	**1**
Loading /capacity (p, t, or m^3)	Medium	1	No accounting	No accounting for impacts of differences in loading capacity	**7**
		2	Accounting for level of loading or restrictions	Accounting for degree of loading and/or potentially reduced load capacity for certain powertrain types for freight (and possibly passenger) vehicles	**3**
Energy consumption (MJ/km)	V. High	1	Representative vehicle types (TC)	Data from type-approval based on a selection of representative vehicle types, e.g. VW Golf, Nissan Leaf, etc.	**3**
		2	Average vehicle test-cycle (TC)	Av. type-approval test data based on market average (e.g. EU monitoring)	**2**
		3	Av. real-world uplift + TC	Av. type-approval data with 'real-world' uplifts applied	**1**
		4	Av. real-world by road type	Real-world performance based on emission inventories methodologies (average) to define variation and split between different road types	**0**
		5	Country real-world by road type	Country 'real-world' performance based on emission inventories methodologies	**1**
		6	Fleet modelling/projections	Vehicle efficiency aligned to specific modelling scenario data (e.g. EC)	**0**
		7	Simple mathematical tractive energy models	Performance of different powertrain / fuel types derived on consistent basis for specific vehicle configurations by complex simulation	**0**
		8	Adjustment for vehicle mass change/loading	Dynamic adjustments to fuel consumption based on variation in vehicle mass or loading (/loading capacity.	**2**
		9	Full vehicle simulation	Performance of different powertrain / fuel types derived on consistent basis for specific vehicle configurations by complex simulation	**2**
		10	N/A	Not defined or not applicable	**0**

Element	Impact	Options			Studies
		#	Type	Description	Studies
Non-GHG tailpipe emissions (g/km)	High	1	New vehicle emission standard	Regulatory emission limits for specific vehicle categories	**3**
		2	Emission standard + RW uplift	Simple accounting for real-world effects using regulatory emission standard values, plus uplift factor	**0**
		3	Regional average, inventory methods	EU average for new vehicle type (fuel/powertrain) based on emissions inventory methods	**1**
		4	Country average, inventory methods	Country average for new vehicle type (fuel/powertrain) based on emissions inventory methods	**0**
		5	Regional inventory, by road type	Regional (e.g. EU) average emissions by road type, e.g. urban/rural/highway	**0**
		6	Country inventory, by road type	Country average emissions by road type, e.g. urban/rural/highway	**0**
		7	Emissions simulation model	Complex emissions model used to derive values (e.g. based on market and/or specific duty/driving cycles, etc.)	**3**
		8	Uncertain/unknown	Not clear in the study	**1**
		9	N/A	Not defined or not applicable	**2**
Fugitive or non-tailpipe emissions (g/km)	**Medium**	1	No accounting	No accounting for non-tailpipe or fugitive emissions	**4**
		2	Accounting for non-tailpipe emissions	Non-tailpipe emissions accounted for in analysis, e.g. tyre and brake wear, evaporative emissions from fuel storage tanks, etc.	**6**
		3	Accounting for methane slip	E.g. based on real-world testing data on emissions from gas vehicles	**0**
		4	Accounting for other fugitive emissions	Accounting for any other fugitive emissions	**2**
Fuel split (%)	High	1	Fixed average ratio	Fixed average share for PHEV/REEVs and dual-fuel vehicles	**0**
		2	Based on specific duty cycle	Alternative options for specific duty cycles	**0**
		3	Based on electric range / battery size (TC)	For PHEV/REEV - based on specific range/battery size + energy consumption calculations for regulatory test-cycle	**2**
		4	Based on electric range / battery size (RW)	For PHEV/REEV - based on specific range/battery size + real-world energy consumption	**0**

Element	Impact	Options			Studies
		#	Type	Description	
		5	Full vehicle simulation	Calculated based on complex vehicle simulation	**1**
		6	Uncertain/unknown	Not clear in the study	**3**
		7	N/A	Not defined or not applicable	**4**
Unladen mass (excl. battery /FC) (kg)	**Medium**	1	Representative vehicle types	Values based on representative vehicles, e.g. from literature or specific models	**6**
		2	Regional vehicle average (e.g. EU)	Average based on EU registrations (all powertrains)	**0**
		3	Country vehicle average	Average based on MS registrations (all powertrains)	**0**
		4	Regional av. + simple battery accounting	Regional average (e.g. EU) with simple methodology to account specifically for different xEV battery sizes (or similarly for FC, H_2 storage)	**0**
		5	Regional av. detailed powertrain derivation	Regional average (e.g. EU) with more complex methodology to account for different powertrain components / sizing + 'glider'	**2**
		6	Vehicle breakdown by detailed sub-component	Vehicle disassembled in mono-material parts at a recycling workshop	**1**
		7	Av. country + simple battery accounting	Average varied for differences between countries, with simple battery accounting	**0**
		8	Av. country detailed powertrain derivation	Average varied for differences between countries, with more complex definition.	**0**
		9	Uncertain/unknown	Not clear in the study	**1**
Vehicle composition (%)	**Medium**	1	Generic literature dataset	Simple composition assumptions based on values from literature	**1**
		2	Average by powertrain type (fixed)	Simple composition defined based on powertrain type. Fixed over time.	**2**
		3	Composition by component (fixed)	More detailed definition based on breakdown of vehicle into sub-systems/components. Fixed over time.	**3**
		4	Average by powertrain type (time)	As above, but with assumptions on changes to composition over time.	**0**
		5	Composition by component (time)	As above, but with assumptions on changes to composition over time.	**3**

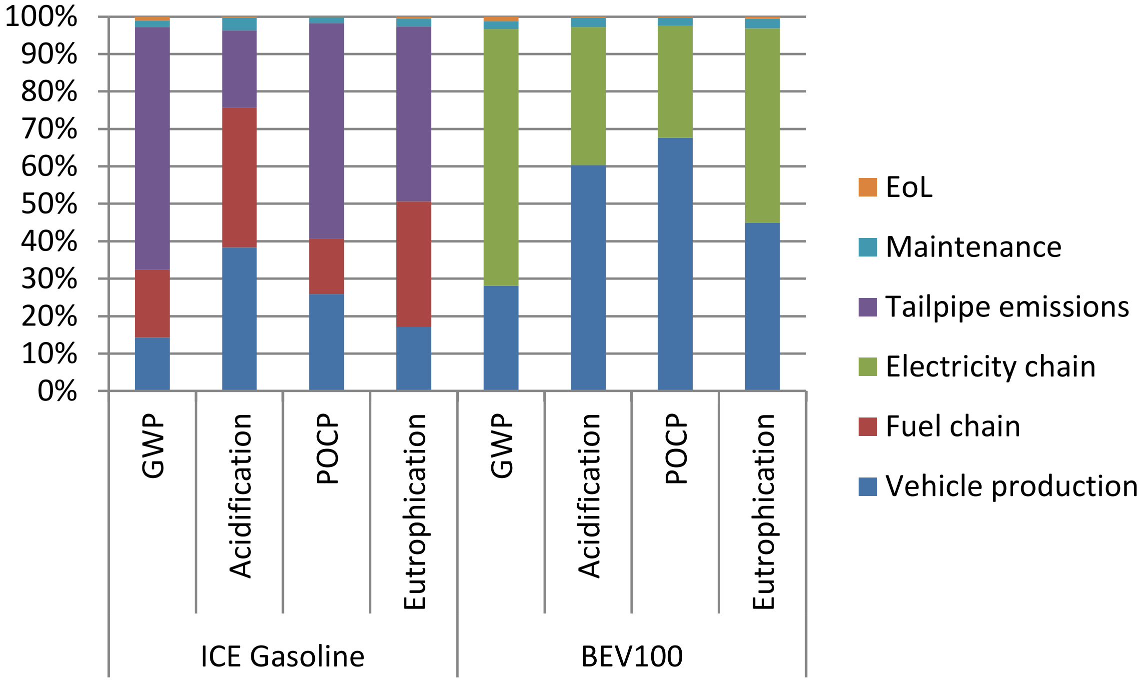
Element	Impact	Options			
		#	Type	Description	Studies
		6	N/A	Not defined or not applicable	**1**
Battery Replacement (#)	**High**	1	Average per vehicle lifetime years	Battery replacements fixed on per vehicle lifetime	**2**
		2	Specific battery cycle life by km	Battery replacement based on battery life in km, and vehicle lifetime km	**5**
		3	Specific battery cycle life by years	Battery replacement based on battery life in years, and vehicle lifetime	**0**
		4	Complex based on battery cycle life, battery size/range and lifetime mileage	Battery replacement based on battery cycle life and size (# cycles, kWh capacity) and vehicle lifetime energy consumption (as defined by mileage and efficiency)	**0**
		5	Uncertain/unknown	Not clear in the study	**2**
		6	N/A	Not defined or not applicable	**1**
Battery mass (kg)	**High**	1	Representative battery types	Batter size estimated based on representative battery types	**1**
		2	Average total fleet or literature review	Estimated based on fleet average/range of models, or literature review	**1**
		3	Simple calculation based on battery % of total weight	Simple definition based on vehicle mass and assumptions on battery % of vehicle weight	**1**
		4	Calculated size/capacity and energy density	Alternative options calculated based on specific battery capacity and energy density assumptions	**2**
		5	Variations based on different battery chemistries/types	Exploration of differences based on specific battery chemistries, e.g. NCA, NMC, LMO, etc	**2**
		6	Variations on battery form (prismatic/pouch/cylindrical)	Exploration of differences for different battery form factors	**0**
		7	Uncertain/unknown	Not clear in the study	**2**
Battery capacity (kWh)	**High**	1	Fixed options	Fixed option(s) defined, e.g. based on review of real/typical vehicles	**9**
		2	Calculated based on range required	Calculated based on combination of range, energy consumption, reserved SoC, other parameters	**0**

Element	Impact	Options			Studies
		#	Type	Description	
Battery energy density (Wh/kg)	**Medium**	1	Fixed options based on xEV type	Adjust energy density dependent on BE or Hybrid	**4**
		2	Fixed options based on battery type	Assumptions varied based on battery type or form factor	**3**
		3	Uncertain/unknown	Not clear in the study	**2**
Battery characteris-ation	**Medium**	1	Generic average	Generic average values used, e.g. from literature or real vehicle examples	**3**
		2	Defined battery type(s)	Batter characterisation based on specific battery types/chemistries selected	**6**
		3	N/A	Not defined or not applicable	**0**
Engine /motor power (kW)	**Low**	1	Fixed representative options	Fixed options, e.g. based on review of real vehicles	**7**
		2	Scaling factors for representative vehicles	Calculated based on scaling parameters to give alternative values for different vehicle types / particular vehicle specification	**0**
		3	Full vehicle simulation	Derived on consistent basis for specific vehicle configurations by complex simulation	**1**
		4	N/A	Not defined or not applicable	**1**

A1.2.2 Vehicle production, maintenance and end-of-life methodology

The hotspot analysis in Section A1.1 has shown that for GHG emissions, which are currently most widely covered in LCAs, the use phase has the highest contribution. For conventional combustion engine vehicles, vehicle production is of lower importance, especially in a comparative LCA. Electric and fuel cell vehicles are associated with a shift of GHG emissions from the use phase to vehicle production. For electric vehicles it can be expected that use phase emissions will decrease with a higher share of renewable electricity generation and thus make vehicle production relatively more important. A higher relevance of vehicle production can also be expected for other impacts categories (see example in Figure A24). While vehicle production in the selected LCA example contributes only about 15 % to the life-cycle GWP impacts for a gasoline vehicle, the contribution to acidification (almost 40 %) and POCP (about 25 %) is significantly higher. For a BEV production may be even dominating total emissions for acidification and POCP (up to 60 % in this example). Vehicle production impacts are therefore of significant importance especially for alternative powertrains and in respect to some impact categories beyond GWP. Therefore, the analysis of differing components between vehicle types (especially batteries) deserves special attention.

Figure A24: Contribution of different life-cycle stages to overall impacts for different impact categories



Source: Data compiled from (ifeu, 2016), electricity split of Germany 2010

A1.2.2.1 Vehicle production and maintenance

A1.2.2.1.1 General overview of approaches

The reviewed LCA studies vary largely in their goal and scope and accordingly also in their level of detail in respect to accounting for impacts from vehicle production. Studies focussing on a use phase comparison rather tend to neglect details in vehicle production and rely on previous studies for an estimate. But there is also a range of more detailed studies either covering the full vehicle cycle or even focussing on specific components. Especially (dedicated) studies on battery production are worth mentioning here, since they have been growing in numbers recently due to the increasing political importance and market relevance of electric vehicles.

General vehicle studies mostly reflect a certain geographic situation in terms of material and electricity mix but hardly consider any variations. Since LCA is often used for comparative assessments, it is no surprise that besides studies on conventional gasoline and diesel vehicles also alternative powertrain concepts, especially electric vehicles (e.g. (ECF, 2017), (Sen, Ercan, & Tatari, 2017), (ifeu, 2016), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015)) are often a focus of vehicle studies in respect to production. Also PHEV, HEV and FCEV have been considered in a range of studies, but to a lesser extent.

As regards the basic material chains for vehicle production, a full modelling of raw material extraction, processing and transportation is rare in full LCAs on vehicles. This level of detail is mostly practiced in dedicated materials studies or for establishment of generic databases (e.g. ecoinvent, GaBi, GREET). The analysed vehicle LCAs rather make use of such generic data from commonly accepted and reviewed databases, e.g. ecoinvent, GaBi.

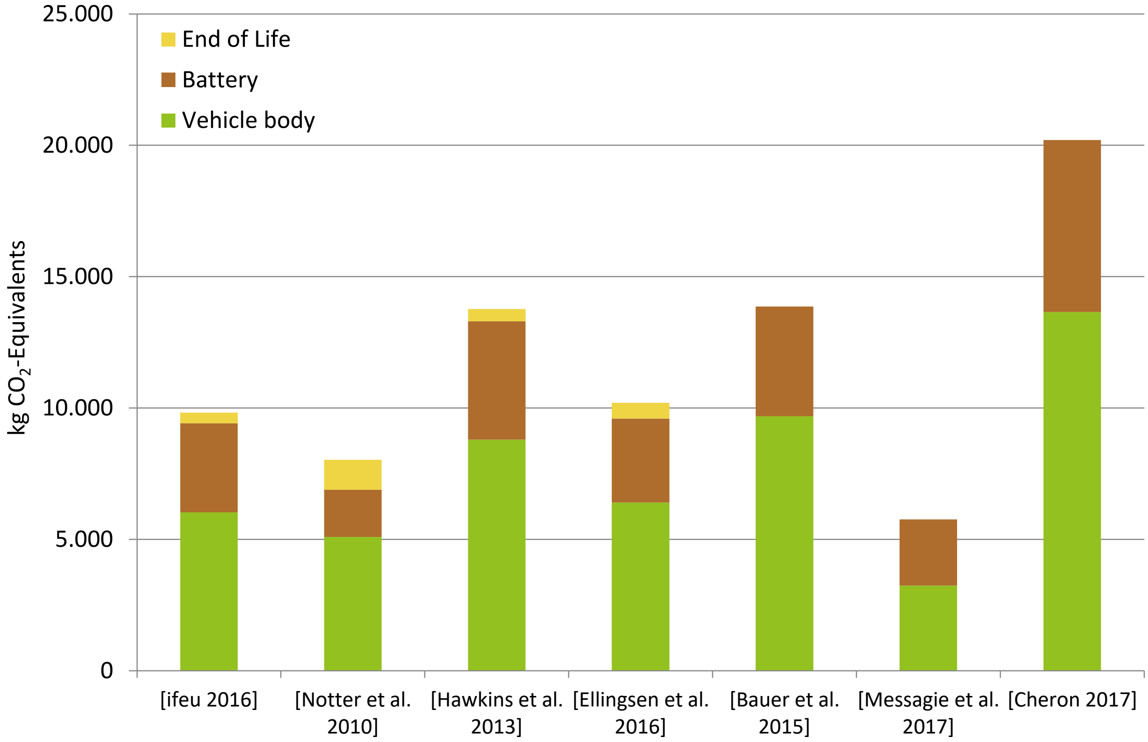
Nevertheless, the bandwidth of the level of detail in respect to vehicle production is still large. The studies at hand can be roughly categorised as follows*:*

4. **Overview/Meta-studies** focussing on the use phase and thus rather using aggregated data for vehicle production which is taken from other sources and only roughly reflects specific differences between the analysed vehicles (e.g. (ADAC, 2018) fully relying of data from (ifeu, 2016)). Such studies are often limited to GHG emissions and do not qualify as full LCAs.
5. **Scientific LCAs on generic vehicle types** in turn often focus on a technology comparison (e.g. (ifeu, 2016), (Hawkins et al, 2012)). Here commonly a higher level of detail on components and materials is considered and further data is often documented. These data, however, usually reflect an average generic situation and do not claim to exactly resemble a specific vehicle model. Input data is compiled from different sources such as other (component) studies, databases as well as OEM and proxy data. Such analyses often use a component based modular approach and consider detailed material compositions and estimates for energy consumption and auxiliary materials used in the production process.
6. The literature review also comprised numerous **OEM studies** on specific vehicle models (e.g. (Audi, 2011), (Mercedes Benz, 2011), (Mercedes Benz, 2014), (Volkswagen, 2010), (Volkswagen, 2014) and (BMW, 2013)). Here mostly primary data from the OEM and their supplier has been used but is mostly not published in detail, except for aggregated results. It can be assumed that further data are available (e.g. from the International Materials Data System (IMDS)) but has to be obtained from the OEM directly.

A more detailed first focus analysis has been undertaken for electric vehicles since they include the vehicle body also applicable to other powertrain concepts and the battery as an important specific component. GHG emission results for vehicle production and end-of-life treatment from selected studies are shown in Figure A25. The range of results for the vehicle body is considerable between slightly over 3 tonnes of CO_2-equivalents (tCO_2e) to over 13 tCO_2e, but can partly be explained by the object of investigation: The highest results are found in (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015) and (ECF, 2017) both analysing a vehicle from the E segment while most other studies focus on the C segment. Also, data for C segment bodies, however, have a considerable range between 3 tCO_2e and 8 tCO_2e which calls for further explanation. This also shows that aggregated data from several studies with different approaches, background data and assumptions can hardly be used for a cross vehicle and powertrain comparison. The need for a harmonised and consistent approach is evident.

For the vehicle production process (1) the use of aggregated meta data for vehicles/components is often used in comparative overview studies focussing on the use stage of vehicles. More detailed studies on vehicle concepts rather make (2) use of differentiated material lists and associated energy consumption and auxiliary substances for generic vehicles or components. Finally, OEM studies tend to (3) use highly detailed manufacturers data for specific vehicle models. As regards vehicle maintenance, often generic data from accepted and reviewed databases (e.g. ecoinvent, GaBi) is used, while more specific bottom-up estimates, e.g. based on commonly replaced components and materials (e.g. tyres, oil, exhaust, brake pads, etc.) are rarely made.

Figure A25: GHG emission results for the production of electric vehicles from selected LCA studies

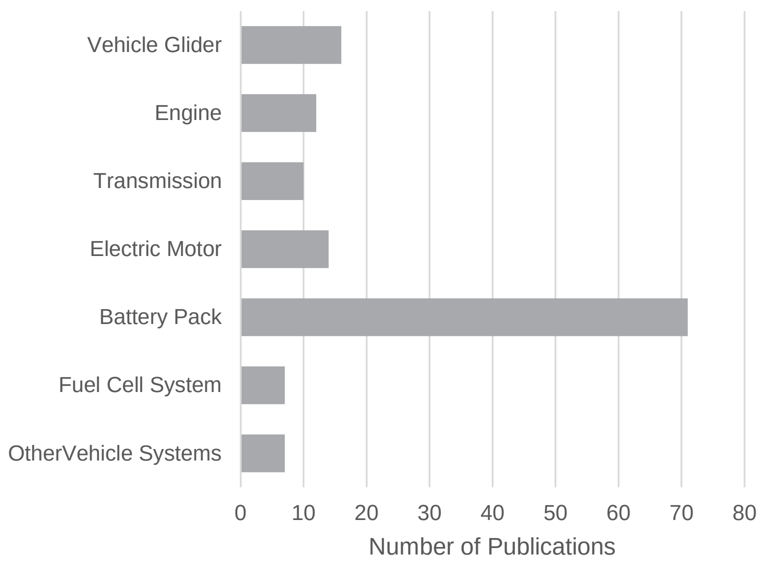


Sources: (ifeu, 2016), (Notter, 2010), (Hawkins et al, 2012), (Ellingsen, 2016), (Bauer, Hofer, Althaus, Simons, & Del Duce, 2015), (Messagie, 2017), (ECF, 2017)

A1.2.2.1.2 Focus on batteries

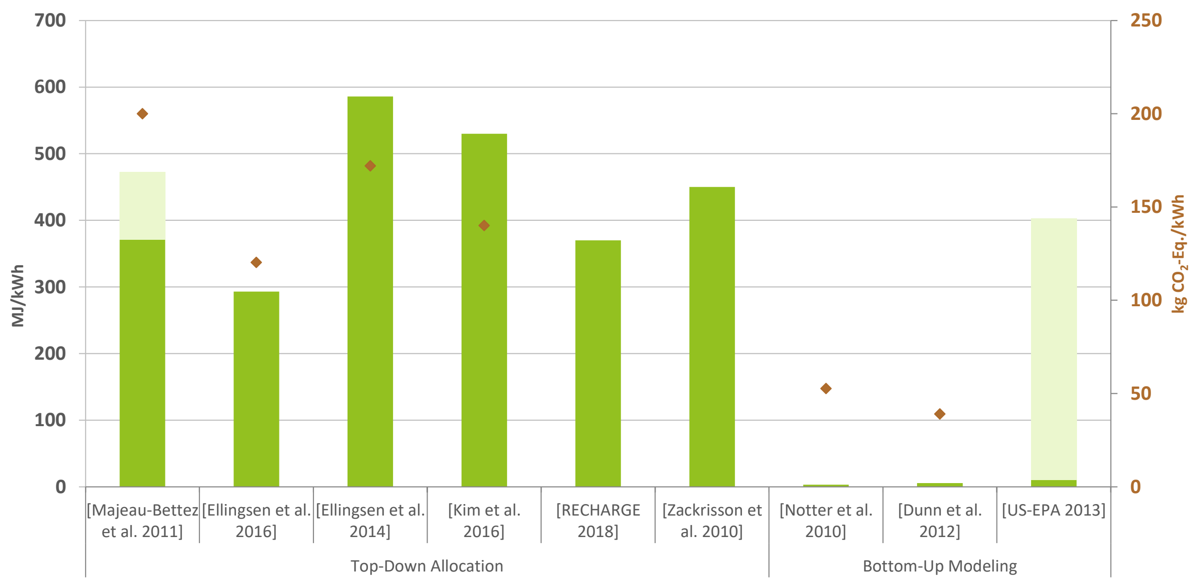
Batteries are the most common focus among the reviewed studies (also) looking at specific vehicle components (see Figure A26). Relevant studies which (partly) use primary data are (ifeu, 2016), (Majeau-Bettez, 2011), (Notter, 2010), (Linda Ager-Wick Ellingsen, 2014). Other studies rely on secondary data. To allow for a comparison, the results have been normalised per kWh of battery capacity. The range is even higher than for vehicle bodies between below 50 kg CO_2-equivalents per kWh (kgCO_2e/kWh) to over 200 kgCO_2e/kWh. The main parameters are energy consumption in the production process, energy density and, to a lesser extent, cell chemistry.

Figure A26: Studies on certain vehicle components



Today, four main lithium-ion cell chemistries are used in electric vehicle batteries: LMO, LFP, NMC and NCA. The material composition is different and correspondingly associated with different environmental burdens. NMC and NCA cells show slightly higher climatic loads in the upstream chains of the materials used, but compensate for those by having higher energy densities. However, since the cathode materials make up only a small part of the total amount of material, the material-side influence of cell chemistry on the overall balance is limited.

Figure A27: Energy consumption for production of kWh of battery capacity in selected studies



Sources: (Majeau-Bettez, 2011), (Ellingsen, 2016), (Linda Ager-Wick Ellingsen, 2014), (Kim, et al., 2016), (RECHARGE, 2018), (Mats Zackrisson, 2010), (Notter, 2010), (Dunn, 2012), (US EPA, 2013)

More important appear to be variations in energy consumption in the production process. Data variations are even higher (see Figure A27) but can first of all be explained by methodological differences. Generally studies using industry data with a top down allocation (e.g. (Majeau-Bettez, 2011) (Linda Ager-Wick Ellingsen, 2014)) consider a much higher energy demand compared to studies which undertake a scientific bottom up modelling of production processes (e.g. (Notter, 2010) and (Dunn, 2012)). Top down allocated industry values are regarded to more accurately reflect the current production situation. Variations still exist but can also be explained by different scales and technology levels of production. It was therefore important to consider a suitable average production status for this study and take into account energy consumption data confirmed by real world operation.

Beyond vehicle production also maintenance leads to environmental impacts associated with the vehicle during the use phase. The topic of maintenance, however, is of lesser importance as has been shown in the hotspot analysis (see Section A1.1.2). Also, the number of studies which actually take into account maintenance has been identified as comparatively small in the literature review. The reviewed papers hardly give any detail on the methodology and data used for modelling maintenance. Due to the low significance of maintenance sometimes generic data from databases are often used.

A1.2.2.2 Vehicle end-of-life processes

A1.2.2.2.1 Recycling and disposal

One area that is not commonly the focus of an LCA study is the vehicle end-of-life phase. However, as shown in the hotspot analysis in Section A1.1, the impacts from the end-of-life stage can be a significant source of differences in impacts between ICEVs and EVs and variations between the methodologies for dealing with EoL processes exist.

This is especially true for the lithium-ion battery of electric vehicles. These batteries may either be

- Simply disposed or partially recycled (discussed in this section); or

- Re-used/re-purposed (e.g. second use as a stationary energy storage) (discussed below).

Depending on the recycling procedures different materials may be recovered for re-use in either new batteries or other applications. The literature review shows that many studies include the end-of-life phase in their assessment (see Figure 2.11), however only a small number of studies explicitly contain specific data on end-of-life (see Figure A29).

The **vehicle disposal** at the end- of-life usually consists of several steps (B.P. Weidema, 2013):

1. First the vehicle is being dismantled manually;
2. Components like tires, batteries and mineral oil are recycled separately;
3. The rest of the vehicle is then shredded, and different waste fractions are separated;
4. Some metals (e.g. steel, aluminium or copper) can be recycled;
5. Other fractions are generally disposed by either municipal incineration (e.g. plastics) or landfill.

The lithium-ion battery can be disposed of in pyro-metallurgical or hydro-metallurgical processes, or hybrid approaches. In commonly applied pyro-metallurgical processes, battery cells are put in a furnace together with a slag forming agent like limestone. The electrolyte evaporates and the carbon containing components (e.g. the graphite anode or plastic components from the casing) are burned and provide additional heat. Direct CO_2 emissions result from this process step. In addition to the slag an alloy containing iron, copper, nickel and cobalt is formed. This alloy may be further refined to separate the different metal fractions (J.B. Dunn, 2014). Impacts from this process step can be high, but are partially being remedied by the secondary material that is gained, especially if a credit for nickel and cobalt is given, since those two materials currently are almost entirely from primary resources. The reduction of environmental impacts and resource use from battery recycling varies much by impact category and recycling approach as illustrated in Figure A28 below from (Hendrickson, 2015), which compares pyrometallurgical recycling (based on the Umicore process) and hydrometallurgical recycling (based on calculations using the GREET model). Accordingly, impact reduction can be as high as 50 % (PM2.5 emissions with hydrometallurgical recycling) and consumption of fossil resources even decreased up to 70 % (use of coal with hydrometallurgical recycling). On the other hand, also higher impacts are possible for some categories such as VOC emissions and electricity consumption.

Figure A28: Resource use and environmental emissions of battery production and recycling (using hydrometallurgy and pyrometallurgy), compared to virgin battery production, for the LMO battery design

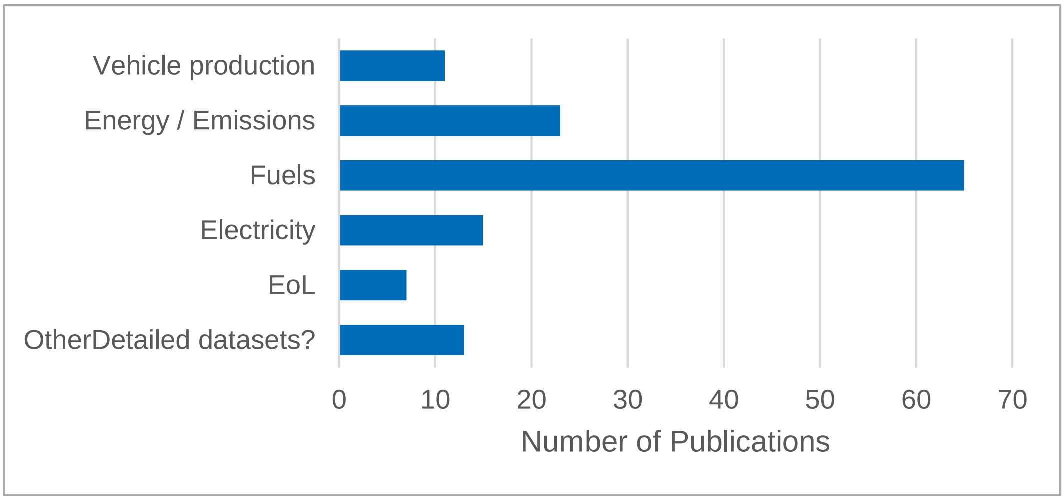
Source: (Hendrickson, 2015)

Besides different processes and data sources, main differences in the environmental impacts reported in literature stem from the end-of-life modelling method. The following basic options for dealing with end-of-life processes (i.e. recycling, energy recovery and disposal) have been identified:

- Closed loop, which hypothetically assumes that materials are (partly) recycled and directly used in the same vehicle, thus avoiding impacts in the material chain accordingly.
- Avoided burden approach (0:100) (also called end-of-life approach) in which the secondary material may (partially) substitute a primary material (elsewhere), which results in a credit usually overcompensating the recycling impacts (e.g. as illustrated for battery recycling above). This method favours recycling and thus supply of secondary materials but does not encourage the usage of secondary material as an input.
- Cut- off approach (100:0) (also called recycled content approach) works the other way around and considers for primary material the full environmental impacts of the material chain, while secondary materials come without any environmental burden. Instead the user receives the full burdens for the waste treatment, but no burdens for recycling. Also, no credit for recycling or waste treatment of by-products is given and a simple cut-off is performed. This favours the use of secondary material as an input, but not the waste treatment with beneficial by-products.
- Allocation at the point of substitution (APOS) performs an economic impact allocation between the primary and secondary usages of a material, thus introduces a partial burden from the previous life at the point where recycled material is used. This method is closely linked to the ecoinvent 3 system model “allocation at the point of substitution”. It requires accurate information on the market values of all primary and secondary products from a product system.
- 50:50 approach which allocates burdens and benefits associated with recycling with a 50% rate. Thus, benefits of recycling are split between suppliers and users of scrap. Here both product systems need to be known to correctly allocate the burdens between the two.

If looking at a steady-state market differences between the different attributional EoL approaches (e.g. cut-off or APOS in ecoinvent) are usually small, if the recycled material at the end-of-life is in the same order of size as the recycled material included as an input into the process, therefore making a cut-off approach the easiest method. Bigger differences for the materials may occur in a consequential model.

Figure A29: Number of studies containing detailed data sets on different life cycle stages



A1.2.2.2.2 Battery reuse/repurposing for second life

The potential for xEV battery reuse / second-life is currently at a relatively early stage of investigation. As a result, there are relatively few studies available on the potential environmental impacts at the end of the life of the battery in the xEV due to battery remanufacturing/repurposing for reuse.

Based on the findings from our work for JRC (Ricardo Energy & Environment, 2019) and also according to (JRC, 2018), despite the availability of some LCAs of second-use of xEV batteries in the literature (e.g. also (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2015), (Casals, AmanteGarcía, Aguesse, & Iturrondobeitia, 2015)), there are not yet any guidelines or harmonized approaches making comparisons difficult. In particular, different system boundaries are observed in the literature, e.g. assessing the whole life of the xEV battery, or only those stages directly affecting the second-use of the xEV battery. A key factor in the analysis is the assumption on the lifetime of the battery, as this is likely to be lower in the second-use application versus a new storage battery.

At a high-level, we have identified four possible alternatives for accounting for the impacts of battery second-life:

1. *Make no accounting in the vehicle lifecycle*: assume any benefits are accounted for in the second-life application, rather than in the vehicle lifecycle;
2. *Compare LCIA for second-life of the battery compared to a specific reference case*: an additional LCA is conducted for *both* the second life of the battery in the chosen energy storage case (e.g. for peak shaving or to enhance home / commercial PV use), *and* also a reference system (e.g. new Li-ion battery, no battery, alternative storage case).
3. *Apply a credit based on assumed equivalent displacement of a new energy storage battery*: In this case an assumption is made that the second-life battery is *only* used to displace the use of an equivalent new battery used in an energy storage application (or a fraction of this due to differences in the storage use lifetime).
4. *Economic allocation using the value of the used battery at its end-of-life*: When the vehicle battery is replaced, the used battery may still have a certain economic value. Using this value, an economic allocation may be done between the burdens for the primary use and the secondary. However, data on the economic value of used car batteries are not readily available and may range between the scrap-value and relevant shares of a new battery, depending on the future demand and durability.

Both cases 2 and 3 imply a consequential approach to the treatment of a possible second life for xEV batteries, and any credits resulting could either be applied entirely to the vehicle chain, *or* shared between the vehicle chain and the energy storage application.

The advantage of Option 2 is that it can help capture differences in impacts for different applications across both systems, however it would require significantly greater complexity to model including the selection of the appropriate 'second-use' application reference/compared case. The advantage of Option 3 is that it removes the need to also select and model one or more reference use cases, only the share of new batteries replaced. However, the draw-back is that alternative use cases for second-life batteries may have different benefits, and the availability of (potentially lower-cost) second-life batteries might create demand in areas where it might not have been otherwise present. In either case, it would be necessary to include in the analysis an accounting for the share of end-of-first-life battery packs (/modules) that could be suitable for second life applications, and whether the potential supply of xEV storage batteries might outstrip potential market demand for them.

Given this area is in quite early stages of investigation, there is considerable uncertainty on such aspects, meaning that treating such assumptions with sensitivity analysis would be important.

The following Table A4 provides a general summary of the key options identified above for the development of the vehicle production, maintenance and end-of-life.

Table A4: Identified options for vehicle production, maintenance and end-of-life stages

Stage	#	Option
Material chains	1	Full modelling of raw material extraction, processing and transportation. Mostly practiced in dedicated materials studies or for establishment of generic databases (e.g. ecoinvent, GaBi, GREET)
	2	Use of generic data from commonly accepted and reviewed databases, e.g. ecoinvent, GaBi. Practiced in most scientific and OEM studies focussing on the full vehicle cycle.
Vehicle production	1	Use of aggregated meta data for vehicles/components. This approach is rather used in comparative overview studies focussing on the use stage of vehicles.
	2	Use of differentiated material lists and associated energy consumption and auxiliary substances for generic vehicles or components.

Stage	#	Option
	3	Use highly detailed manufacturers data for specific vehicle models.
Vehicle maintenance	1	Use generic data from accepted and reviewed databases (e.g. ecoinvent, GaBi).
	2	Use more specific bottom-up estimates, e.g. based on commonly replaced components and materials (e.g. tyres, oil, exhaust, brake pads, etc.).
End-of-life processes	1	Closed loop, hypothetically assuming direct recycling and reuse in same vehicle
	2	Avoided burden approach (0:100) with credits for recycled materials.
	3	Cut-off approach (100:0) with full allocation of the material chain to primary materials and while secondary materials come without any environmental burden.
	4	Allocation at the point of substitution (APOS), performing an impact allocation between the primary and secondary usages of a material
	5	50:50 approach which allocates burdens and benefits associated with recycling with a 50% rate.
Second Life	1	No credit for battery second life.
	2	Credit applied based on comparison of LCIA of second use battery versus an alternative reference case (i.e. second use case is specifically modelled also).
	3	Credit applied based on the avoided use of an equivalent new energy storage battery.
	4	Economic allocation using the value of the used battery at its end-of-life in the vehicle

A1.2.3 Fuel production chains

Literature review provided a solid overview of environmental impacts associated with fuel production, covering the wide range of gaseous and liquid fuels which are currently used in the European vehicle fleet, or might be used in the future. The European fuel mix is currently comprised predominantly of fossil diesel and gasoline, with a number of other fuel types present in smaller proportions. These alternative fuel types include biofuels, alternative fossil fuels, and more recently fuels made from renewable electricity (e-fuels or renewable fuels of non-biological origin – RFNBOs). The fuel mix varies according to region; by vehicle type; and by time of year as winter and summer fuel requirements can vary.

Emissions from the fuel cycle can be considered on a well-to-tank (WTT) or well-to-wheel (WTW) basis. A WTT methodology includes the production of the raw material or ‘feedstock’ used for fuel production (e.g. crude oil, corn, natural gas), transport of that feedstock to a processing facility, processing / conversion into the fuel, and transport of the fuel to a refuelling station. All inputs and emissions during that process (including accidental leakage) are within scope, and the functional unit is one unit of fuel delivered to the tank of the vehicle. A WTW assessment includes all of the WTT impacts, and in addition the combustion of the fuel within the vehicle, primarily emissions of GHG and other air pollutants. In this study LCA impacts of fuels are reported on a WTT basis, with a functional unit of 1MJ of blended fuel. When GWP is reported, CO_2 emissions from combustion of the fuel are also included in the calculation. This does not provide information on the km travelled or tonnes of goods moved, which requires integration with vehicle efficiency, operation etc. and is considered in the vehicle module.

The environmental impacts associated with fuel production can be substantially different depending on whether that fuel is produced from a biogenic feedstock, fossil feedstock, or electricity, and the key methodology questions can also be quite distinct for these fuel types. Following the literature review, a large number of fuels were considered for inclusion in the study, as summarised in Table A5.

Table A5: Summary of broad categories of fuel considered at the literature review stage

Fuel categories	Types of feedstocks	Types of fuels produced
Fuels produced from primary fossil feedstocks	Crude oil Natural gas Electricity (fossil)	Liquefied petroleum gas (LPG) Gasoline Diesel Compressed natural gas (CNG) Liquefied natural gas (LNG) Non-renewable Hydrogen
Fuels produced from waste (secondary) fossil feedstocks	Fossil fraction of MSW/RDF, C&I waste Fossil waste plastic / rubber Industrial process waste gases	LPG Gasoline Diesel SNG Hydrogen
Fuels produced from crop/forestry-based (primary biogenic) feedstocks	Oil crops (e.g. rapeseed) Macroalgae Microalgae Sugar crops Starch crops Energy crops (lignocellulosic) Short rotation forestry	Ethanol (and other alcohols) Fatty acid methyl ester (FAME) Hydrotreated vegetable oil (HVO) Synthetic diesel such as Fischer-Tropsch diesel LPG Synthetic natural gas (SNG) Hydrogen
Fuels produced from waste / residue (secondary) biogenic feedstocks	Used cooking oil and waste animal fats Tall oil pitch Food and feed crop residues Forestry residues and waste wood Wet manure Sewage sludge Biogenic fraction of MSW/RDF and C&I waste Black & brown liquor Crude glycerine	Ethanol (and other alcohols) Fatty acid methyl ester (FAME) Hydrotreated vegetable oil (HVO) Synthetic diesel such as Fischer-Tropsch diesel LPG Synthetic natural gas (SNG) Hydrogen
e-fuels	Electricity (Renewable) CO_2	Hydrogen Bio-SNG Synthetic diesel (also known as power to liquids, PtL)

Coal-based technologies were not considered in this study, given their limited deployment in the EU and significantly higher life-cycle greenhouse gas emissions, compared to other fossil fuels (About 195 gCO_2/MJ vs approx. 104 gCO_2/MJ for conventional fuels (Lehman, 2018)). Coal-based technologies may reduce their GHG emissions when coupled with carbon capture and sequestration (E4tech, 2018), but no such industrial project is expected to be deployed in the European Union in the foreseeable future.

A1.2.3.1 Fuels produced from primary fossil feedstocks

A1.2.3.1.1 System boundaries

A major difference between fossil fuels and certain types of renewable fuels (e.g. biofuels, biogas, renewable hydrogen) concerns the consumption phase: The carbon embedded in hydrocarbon molecules is from fossil origin and upon fuel combustion, is released into the atmosphere as CO_2 or CO, thus adding to the atmospheric stock of greenhouse gases and contributing to climate change. Crop-based or waste-based biofuels, when combusted, emit the carbon atoms that were absorbed by plants, thus creating a neutral carbon loop. Therefore, emissions during the use phase are considered null for biofuels (and to some extent renewable hydrogen, given the absence of emissions in fuel cell cars, other than water). On the contrary, emissions during the combustion phase constitute one of the biggest shares of the life-cycle emissions of fossil fuels. In other words, a well-to-tank approach is adequate to capture most of the life-cycle emissions of a biofuel or renewable hydrogen, for which most life-cycle emissions are found during the raw material production and processing stages. In turn, assessing life-cycle emissions of fossil fuels on a well-to-tank basis would leave a significant share of emissions outside the scope and make a comparison with biofuels meaningless. A meaningful comparison between fossil and alternative fuels should therefore include the emissions from fuel combustion.

A1.2.3.1.2 Multi-functionality/Co-products

Oil refineries generate multiple co-products at different stages of the refining process, including but not limited to diesel, gasoline, jet fuel (kerosene), heavy fuel, naphtha and chemicals. Therefore, inputs (energy, water, chemicals) and emissions must be allocated onto the different co-products. Several allocation methods exist based on mass, energy content or market value. JEC (JEC - Joint Research Centre; EUCAR; CONCAWE, 2014a) is using the CONCAWE model, which uses a "simultaneous constraints" approach, whereas a model developed by ifeu is based on an average energy allocation approach.

A1.2.3.2 Fuels produced from secondary fossil feedstocks

The importance and potential impact of 'counterfactual' use of secondary fossil feedstocks such as CO-rich waste gases is highlighted in the JRC guidance to calculating default values for the FQD (JRC, 2016) as well as in various JRC presentations to expert groups. Depending on the existing use of the feedstocks, the burden associated with replacing those products can dwarf the life cycle impacts of the actual processing of the feedstock into a transport fuel (E4tech, 2018) and therefore will need to be carefully considered in an LCA of these fuels.

Generally, the counterfactual use of gaseous waste fossil feedstocks is easier to determine than that of solid waste fossil feedstocks. This is because gaseous feedstocks are produced and either emitted to air (venting or flaring) or directly converted to another energy vector at a specific plant ('point source'). The emission or conversion immediately at the point of origin are dictated by the combination of their generally low energy density and other technical requirements associated with storage and transport of gases that make this economically infeasible.

Solid wastes, on the other hand, have to be removed from site (domestic and commercial) for disposal either in landfill, incinerators or various recycling processes and can be stored, transported, collected and traded easily. Due to this 'pool source' nature, the origin and/or counterfactual fates are difficult to assess for the purposes of a fuel LCA. It is clear however that in the case of mixed plastics waste streams the environmental impacts of a selection of end of life processes (landfill, energy recovery, material recycling) can vary widely (WRAP, 2008). Figure A30 is a summary taken from (WRAP, 2008) and shows the relative ranking of end of life scenarios in a variety of impact categories (rank 1 = best, rank 16 = worst, with the best 4 highlighted green, the worst 4 highlighted red).

A similar picture is presented for waste tyres (European tyre & rubber & manufacturers' association, 2015), where data shows that approximately 50% of used tyres in the EU are recycled, with the other 50% going to energy recovery. Further detail for Germany shows that in 2014, 27% of tyres were re-used after re-treading, 35% recycled after granulation, and 37% ended up in energy recovery. One LCA (Clauzade, Osset, Hugrel, Chappert, & Durande, 2010) indicates significant differences in the GHG as well as water consumption savings when used tyres replace coal in cement kilns compared to replacement of other materials for sports track surfacing, or use in district heating plants.

The important take-away from these studies is therefore that for traded ('pool source') waste fossil feedstocks the consideration of their counterfactual use can lead to important variability in the life cycle results across multiple impact categories but is difficult to determine. It is particularly important for waste fossil feedstocks that the system boundary around the feedstock is carefully defined, to ensure that any potential emissions savings are not double-counted between the primary process which produces the waste, and the fuel production process which uses the waste.

Figure A30: Summary of life cycle assessment results of the comparison of end of life processing scenarios of a mixed plastics waste stream.

Scenario	GWP	Solid Waste	Energy	HTP	EP	POCP	AP	ADP	OLDP
A (Landfill)	15	16	16	16	16	16	16	16	16
B (Incineration)	16	1	8	15	10	15	15	15	2
C (SRF)	11	2	1	14	2	12	11	1	10
D (BP pyrolysis)	14	12	4	2	8	13	13	14	3
E (Ozmotech pyrolysis)	13	15	3	3	1	11	12	13	1
F (Redox agent)	12	4	2	4	13	14	14	5	9
G (Stadler & Titech)	1	5	5	5	3	6	4	3	6
H (Stadler & Pellenc)	4	7	7	11	5	8	8	7	4
I (Stadler & Qinetiq)	7	14	10	13	7	10	10	12	5
J (Stadler & Sims)	2	6	6	6	4	7	5	4	7
K (KME & Titech)	5	8	9	12	6	9	9	9	8
L (Stadler & TLT)	6	10	12	8	11	3	2	6	11
M (Swiss Polymera)	3	3	11	1	9	1	1	2	13
N (B+B)	9	13	14	10	14	5	6	10	14
O (Stadler & Herbold)	10	11	15	9	15	4	7	11	15
P (Stadler & Flottweg)	8	9	13	7	12	2	3	8	12

Source: (WRAP, 2008) *GWP = global warming potential, HTP = human toxicity potential, EP = eutrophication potential, POCP = photochemical ozone creation potential, AP = acidification potential, ADP = abiotic depletion potential, OLDP = ozone layer depletion potential*

A1.2.3.2.1 Fuel combustion

When fuels produced from waste fossil feedstocks are combusted in a vehicle engine, the emissions released are the same as for the combustion of any other fuel. However, there are various approaches to how those emissions are allocated to the fuel, which can produce substantial variation in the results.

Some arguments suggest that the emissions from fuel combustion should be assigned to that fuel, because it is fossil CO_2, which is being released to the atmosphere, making a net contribution to global warming.

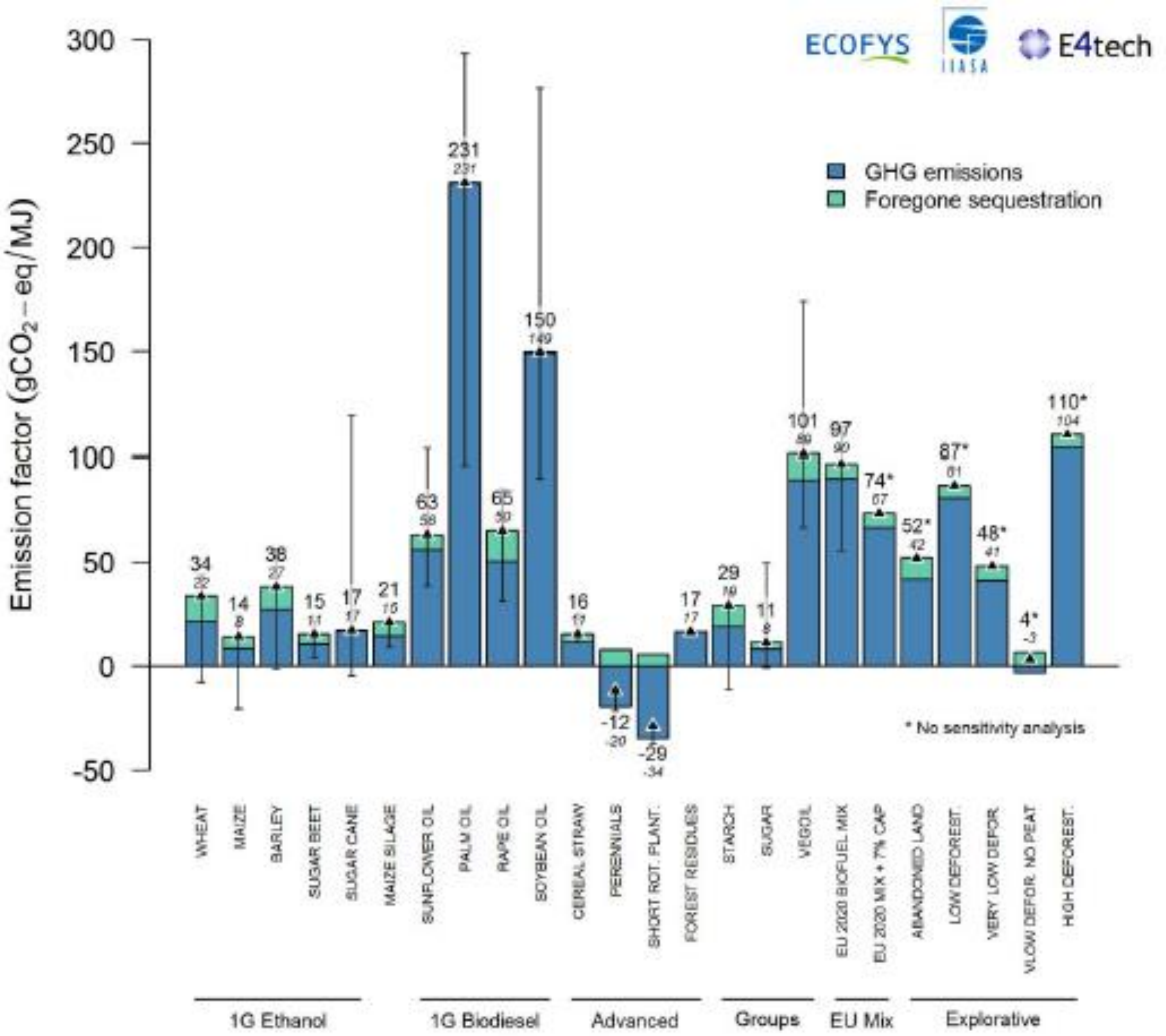
On the other hand, some arguments suggest that as the feedstock was 'waste' and the carbon would have been released to the atmosphere anyway, then the environmental impact of its release does not need to be assigned to the fuel. Considering in more detail the counterfactual uses of the feedstocks, some feedstocks truly would have been released to the atmosphere (e.g. waste industrial gas that was previously flared) whereas some would not have been released to the atmosphere (e.g. waste fossil plastic that is sent to landfill). Therefore, if a consequential approach is taken, it is possible to assign the combustion emissions the fuel only if they are truly 'additional', i.e. would not have otherwise taken place (E4tech, 2018). However, as outlined in section A1.1.3.4.2, understanding the counterfactual use of the feedstock can be challenging and very uncertain.

A1.2.3.3 Fuels produced from primary biogenic feedstocks

A1.2.3.3.1 Land-Use Change

For any given fuel there is a high degree of uncertainty around the environmental impacts from land use change. Direct land use is specific to the location in which a crop is cultivated, therefore including these impacts in LCA requires either knowing the specific location of cultivation of that crop, or taking an average or generalisation to an entire crop type or region. The indirect land use change can only be assessed by understanding and modelling economic and trade flows globally, generally using complex models which are not transparent to the non-expert or policy-maker. Uncertainty in input values and in modelling causality give a large uncertainty range around LUC emission figures, as illustrated in Figure A31. Currently indirect impacts are reported but not included in fuel GHG assessments under EU regulation, but they are included in GHG assessments for the California Low Carbon Fuel Standard (LCFS).

Figure A31: Land use change emissions for a number of biofuel production scenarios, with and without foregone sequestration (Error bars are included).



Source: (Valin, et al., 2015)

A1.2.3.3.2 Fuel production/feedstock processing

A number of different processes can be used to convert crops into fuels, depending on the type of crop and the desired fuel. The environmental impacts from fuel production are generally dependent on the energy and material inputs to the process, and for some fuels the environmental impacts from the fuel production can be substantial (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b).The overall impact can vary substantially depending both on what inputs are required and how they are produced. For example, in (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b) chains WTET3 and WTET2 have roughly the same energy demand for processing, but WTET3 represents ethanol production from wheat with energy provided by a lignite-fired CHP plant, whereas the WTET2 represents energy provision by a natural gas fired CHP plant. The impact of this change is over 20 gCO_2e/MJ.

As of 2018, the greenhouse gas intensity of biofuels has to be reported using the methodology set out in Directive 98/70/EC and Council Directive (EU) 2015/652. This reporting will allow obtaining an overview of the different methodologies chosen on average, and the GHG obtained.

In addition, many biofuel production processes produce more than one product or co-products, therefore the allocation method adopted can have a big impact on the environmental impacts assigned to the fuel of interest. A number of different allocation methods are seen in the literature: studies following the RED methodology such as (Fehrenbach & Köppen, 2012) adopt energy allocation, but a system expansion methodology can also be used (e.g. (Khoshnevisan, et al., 2018), (JEC - Joint Research Centre-EUCAR-CONCAWE, 2014b) or physical or economic allocation (Munoz, et al., 2013). The choice of allocation method can have a substantial impact on results (Sandin, Royne, Berlin, Peters, & Svanstrom, 2015). For co-products which have a very low energy value but a substantial mass or economic value, such as char, the choice between methods is particularly important. The system expansion method relies on knowing or assuming which product the biogenic co-products will be replacing and hence what their credit should be.

A1.2.3.3.3 Fuel Combustion

The point emissions from fuel combustion in an engine are the same, for a given fuel type, regardless of whether that fuel is produced from biological or fossil feedstocks. Nevertheless, assigning environmental impacts to emissions from biofuel combustion, is dependent on how biogenic carbon is treated in the LCA methodology.

In the production of biofuels, biogenic carbon is taken up by living biomass, converted into a fuel including some release of carbon during the process, and then released when that fuel is combusted in the engine.

The majority of biofuel LCA studies consider the uptake and release of biogenic carbon across a well-to-wheels (WTW) assessment to net to zero, and therefore do not explicitly model biogenic carbon flows. This is the approach adopted by the European Commission (European Union, 2009). Nevertheless, (Wiloso, Heijungs, Huppes, & Fang, 2016) challenge this assumption of neutrality and note that in some cases, for example when the carbon emission occurs in different forms (CO_2 vs. methane) there is a substantial difference between the results obtained with the carbon neutrality assumption and those obtained with a complete inventory of all biogenic carbon. This may be particularly important if taking a consequential approach to waste biomass, as avoided carbon release might be substantially in the form of methane, whereas emitted carbon is likely to be in the form of CO_2.

Moreover, there is concern about taking a ‘net neutral’ assumption compared to explicit modelling of biogenic carbon flows when there is a large time difference between the uptake and release of biogenic carbon, for example in the case of using wood to produce biofuels. This impact is also called ‘carbon debt’, and has been highlighted by researchers as a concern, because there is an immediate need to decarbonise, but it may take many years to re-assimilate the carbon that was released on felling and combustion of trees. Ultimately the net neutrality of biogenic carbon uptake and release is not being disputed in the carbon debt argument, but there is concern that the impacts of these CO_2 emissions differ depending on when in time they occur. The time dependency of carbon uptake and release has to-date not been extensively considered in LCAs, which generally aim to provide a ‘snapshot’ of the system in time, although research is ongoing into the development of methodologies to account for these impacts, for example by Porsö (Porso, 2017).

In addition to CO_2 emissions from fuel combustion, there may be other emissions from the exhaust, including those which contribute to GWP including N_2O and CH_4, and those which contribute to other impact categories such as human health, for example particulates and NOx. Conventional WTW approaches often do not capture or include these tailpipe emissions, which may contribute to a range of environmental impacts. When comparing between two fuels which are chemically the same or very similar (e.g. HVO and conventional diesel), the difference caused by omitting these emissions is likely to be small. However, when comparing between different fuel types, or combustion in different engines, or to understand the absolute (rather than relative) environmental impact it is important to include all emissions from combustion.

A1.2.3.4 Fuels produced from secondary biogenic feedstocks

A1.2.3.4.1 Allocation of emissions to wastes/residues

There is not one single approach to determine what constitutes a 'waste' or 'residue', and indeed variation is seen between different EU MSs in their classification of some materials as wastes or co-products. Nevertheless, there is generally agreement between LCA practitioners that for material which is a waste or a residue, a different approach to assigning emissions should be adopted compared to feedstocks which have been cultivated specifically for the purpose of fuel production. Given the substantial impacts potentially associated with cultivation of biomass feedstocks (see section A1.1.3.5.3) the choice of method can have a substantial impact on the overall fuel environmental impacts.

Different approaches are seen in the literature for the allocation of emissions to wastes or residues used in biofuel production:

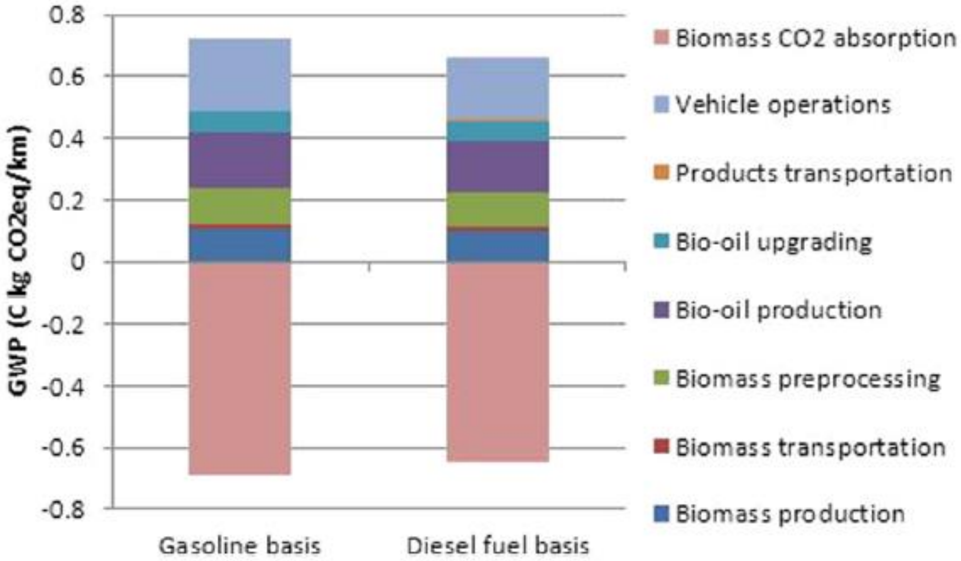
1. Assume that all emissions from the production of the waste / residue are allocated to the primary product which resulted in that waste / residue being produced.
2. Allocate some emissions to the waste / residue from the primary process in which it was produced.
3. Assign the waste / residue with the environmental impacts of diverting it from its existing use.

Approach 1 is that followed by the RED methodology, which means that the feedstock enters the production process with no emissions allocated to it. Many LCA studies therefore follow this approach, as the RED legislation is an important driver for assessments of fuel sustainability. One study (Whittaker & al., 2014) conducts an LCA of bioethanol produced from wheat straw following approach 1, allocating no emissions to the straw used in the process. The authors also conduct a sensitivity analysis to understand the impact of allocating the cultivation emissions between wheat grain and wheat straw according to both energy content and price (approach 2). Using approach 1 they calculate that the GHG saving of ligno-cellulosic bioethanol is 91%, whereas when cultivation emissions are allocated on a cost basis the saving drops to 84% and with allocation on an energy basis it is 76%. If approach 1 is adopted, it is important to clearly define the system boundary, so that any additional transport or processing that has to happen to the waste as a result of it being used for fuel production are included within the LCA. Adopting approach 1, the definition of what biomass is a waste / residue, as opposed to simply being a co-product of an agricultural production system, is crucial to the overall environmental impact of the fuel.

Approach 3 is a consequential approach (equivalent to the counterfactual uses approach considered in Environmental impacts from waste fossil feedstocks A1.1.3.4.2 for waste fossil fuels), and is adopted in a number of studies, including for example (Zhang, Hu, & Brown, 2013). This consequential approach is adopted by the Renewable Fuel Standard (RFS) in the USA for policy purposes, so that when for example biogas from landfill sites is used in fuel production a credit is given to the fuel for the avoidance of leaked or flared landfill gas. Positive or negative environmental impacts can be assigned to the biomass feedstock if consequential approach 3 is adopted.

For example, (Zhang, Hu, & Brown, 2013) assesses the LCA of fuels produced from corn stover, and emissions are assigned to the corn stover based on the additional fertiliser that is required on the fields due to removal of the stover. This can contribute a significant amount to the GWP of the fuel. On the other hand, under the Californian Low Carbon Fuel Standard (LCFS) bioCNG from animal waste has been certified with a carbon intensity of -255 gCO_2e/MJ, including a credit for avoided methane emissions from management of the animal waste ((CARB), 2018).

Figure A32 Contribution of unit process to global warming for gasoline and diesel fuel production from corn stover



Source: (Zhang, Hu, & Brown, 2013)

Adopting the consequential approach relies on knowledge of what the 'alternative' use of that waste or residue would have been. This may be straightforward for a location-specific biofuel LCA where the feedstock can be traced back to a defined farm or region. However, it becomes increasingly challenging as the geographical scope of the LCA widens, as there may be a number of different alternative uses of the feedstock, and it may not be possible to trace which is the most appropriate.

A1.2.3.4.2 Fuel combustion

As for crop or forestry-based biofuels (section A1.2.3.3), many LCA methodologies for waste-based biofuels do not explicitly consider the release of CO_2 when the fuel is combusted on the grounds that carbon uptake and release over the biofuel lifecycle is broadly net zero. As discussed in section A1.2.3.3 there are some cases where this assumption breaks down. This may be particularly important if taking a consequential approach to waste biomass, as avoided carbon release might be substantially in the form of methane, whereas emitted carbon is likely to be in the form of CO_2.

If explicitly considering biogenic carbon uptake and release, some biogenic carbon uptake should be allocated to biomass regardless of whether it is a primary product or a waste. For example, in (Zhang, Hu, & Brown, 2013) biogenic carbon taken up by the whole crop is allocated to corn stover according to its percentage of the overall mass of the crop.

A1.2.3.5 E-fuels

A1.2.3.5.1 System boundaries

While a Well-to-Tank approach may be well suited to compare impacts of fuels used in Internal Combustion Engines (e.g. diesel, gasoline, biofuels, methane, etc.) or to compare different hydrogen production modes, this might not be the case when comparing hydrogen to other road transport fuels. Fuel cells use hydrogen to produce electricity used in an electric powertrain, which implies a very different energy system than in an ICE. Comparing hydrogen to other fuels via an LCA approach would therefore be meaningful by using Well-to-Wheel system boundaries, as it would allow directly comparing vehicle performance. Therefore, similarly to electric vehicles (batteries), an intermediary comparison of hydrogen and other road fuels based on Well-to-Tank boundaries would likely not provide any meaningful outputs given the high energy density of hydrogen, compared to gasoline or diesel.

Functional units would depend on the defined system boundaries. In a WTT system, the functional unit would be expressed in MJ or kg of H_2 produced. If storage and compression are included in the scope, the functional unit will also include the pressure level (e.g. MJ H_2 at 350bar).

Finally, the production and end-of-life of infrastructure and equipment (e.g. electrolyser, steam reforming unit) may be considered in the scope of the LCA, as they may represent a significant share of resource/energy consumption and emissions.

A1.2.3.5.2 Electricity source

In case of hydrogen production via electrolysis, the origin of electricity used to run the electrolyser will significantly influence the LCA results, depending on the share of renewables in the national electricity mix. Country-level data will provide more accurate results, but may not be as robust and comprehensive as, for example, an EU-27 average.

The general functioning of electricity markets in the country will also impact the operability of the electrolyser, given that its functioning might only be profitable at certain times of the day, thus requiring frequent shutdowns and start-ups leading to an increase in energy consumption.

A1.2.3.5.3 Other e-fuels

To date, renewable H_2 is the main e-fuel produced today. Technologies combining renewable H_2 and captured CO_2 to produce renewable methane, methanol, ethanol, diesel and derivatives are still to demonstrate economic viability, given the additional steps required, on top of hydrogen production. It is anticipated, that the environmental impacts of other e-fuels will have impacts additional to those simply resulting from hydrogen production, likely having higher process energy consumption, GWP and water consumption. The use of patented enzymes, microbes and catalysts (for methanation or fermentation) may induce additional environmental impacts, due to their manufacturing. Intellectual property issues may make primary data difficult to obtain.

A2 Appendix 2: Summary of the Delphi Survey and data validation exercise

A2.1 Summary and conclusions from Delphi Survey Round 1 [and Stakeholder Workshop]

Provided as a separate PDF file alongside this report.

A2.2 Summary and conclusions from Delphi Survey Round 2

Provided as a separate PDF file alongside this report.

A2.3 Summary of feedback from the data validation exercise

During the course of the study, stakeholders were also invited to participate in two data validation exercises. The objective of these was to obtain expert input on key data and assumptions on vehicle parameters where there is greater uncertainty (e.g. relating to new powertrain components, mileage or electric range assumptions, etc) for the application of the LCA methodology.

A2.3.1 First data validation exercise: specification of reference vehicles

The first data validation exercise focused on the specification of the seven reference vehicles. In total, nine responses were received and suggested improvements to the assumptions on the shares or specific quantities of certain materials used in the glider and key components (e.g. engine) of the baseline vehicles (e.g. metals, fluids, etc). Based on this feedback, the team adjust the assumptions where possible. If no specific data was provided and only a qualitative comment was made, the team requested further data or reviewed additional sources to update the estimates. In particular, the assumption on the overall shares of metals, fluids, rubber and aluminium were revised. Specific input was also provided on the composition of exhaust systems in LDVs which was subsequently implemented in the analysis.

In addition to the input provided, a few stakeholders also submitted questions or expressed concerns over the methodology choices, including:

- The representativeness of the baseline vehicle: stakeholders argued that, in reality, material composition of a vehicle class varies widely, linked to the technical specifications of each model (e.g. safety, comfort, design, etc). There are important differences between vehicles of different OEMs and even within the same OEM for different vehicle variants and, therefore, the average material composition does not adequately represent the vehicle class;
- The assumption of the same material composition of the glider for all powertrains: stakeholders claimed that this is not representative because xEVs have specific e-platform strategies;
- Definitions of certain materials, e.g. definition of average plastic.

To these, the team clarified the assumptions and referred to the objectives of the study that led to these decisions as well as the responses to the Delphi survey where a number of these methodological choices had already been discussed and validated by stakeholders.

A2.3.2 Second data validation exercise: specification and operation of alternative powertrains

The second exercise invited stakeholders to provide feedback on a number of key assumptions and scaling factors on the alternative powertrains (i.e., xEV and AFV storage and range assumptions, engine and motor scaling factors, fuel cell system and battery system assumptions, efficiency and activity assumptions).

In total, eight responses were received and included suggestions to improve the following assumptions:

- The battery capacity and electric range of xEVs, including increasing the range of REEVs, and use fixed assumptions for HEV battery capacity;
- The efficiency and activity of REEVs vs PHEVs;
- The CNG/LNG configurations, including the fuel/tank weight ratios and energy efficiency assumptions as well as to exclude CNG from the long-haul/artic applications;
- The fuel cell system assumptions, including on the scaling of power relative to the equivalent ICEV, on the power density of the fuel cell stack, and on the lifetime of the fuel cell.

Where our assumptions deviated from the feedback provided, amendments were made. In addition, some of the input also expressed some concerns over the assumptions on future improvements (e.g. increase in range, energy density of batteries, rate of shift to solid state batteries). These have been considered in the sensitivity analysis also carried out in this study.

A2.4 Feedback received at/after the final stakeholder meeting

The following broad types of feedback/questions were received in response to the presentations at the final stakeholder meeting:

1. *Feedback relating to the presentation and use of results/study objectives*: input received from stakeholders included questions and suggestions on the presentation of results for certain powertrains or fuel types (e.g. gas fuelled vehicles, fuel chains analysed using substitution to address process multifunctionality) as well as comments on the overall objectives of the work. This feedback was considered and directly addressed in the main report and appendices to the extent possible.
2. *Questions/feedback requesting information on key assumptions*: several questions received from stakeholders focussed in particular on the assumptions underlying the key results. Information on these assumptions is now clearly and transparently provided in the main report and appendices.
3. *Feedback relating to the accuracy of assumptions or results*: comments received also questioned some of the assumptions and suggested alternatives (e.g. assumptions regarding battery performance, lifetime mileage, exhaust emission factors). A number of these comments were taken on board and led to changes in key data and calculations. The assumptions and results have been updated accordingly in this report.
4. *Other feedback and questions*: other comments and questions received were more specific and are therefore summarised in Table A6 below which also includes clarifications from the project team.

A summary of responses from the project team to key questions and feedback received at/after the final stakeholder meeting that is not directly addressed elsewhere in the main report or appendices is summarised in the following Table A6 below.

Table A6: Summary of responses to generalised feedback/questions based on the final stakeholder meeting presentations

#	General question or comment	Response	See section
G	***General Methodology/Background LCI***		
1	Are mining activities to extract materials for vehicles included in the scope of this study? And has the study considered the potential for the increased scarcity of some materials to lead to higher mining efforts?	Mining activities are included in the impact factors used for the materials extracted from the background LCI databases (mainly Ecoinvent 3). Unfortunately, due to the breadth of the coverage of our study it was not feasible to explore potential future implications of demand on the impacts from resource production. Against the backdrop of the broad scope of the study, and based also on the stakeholder consultation on the methodology, it was decided to mostly use an overall consistent attributional approach as a solid baseline impact assessment, which also follows the recommendation in the ILCD handbook. For the fuel chains, consequential approaches are used as a sensitivity to the default approach, to assess the impact of diverting secondary feedstocks from their counterfactual use to fuel production. This approach of using consequential elements only for selected stages is also in line with the analysed LCA literature, where almost no studies apply the consequential approach to the whole vehicle life cycle. Understanding and modelling the potential impacts of demand on resources is also hugely complex, and would be better served in a dedicated study to consider these aspects for key materials.	Appendices: A3.7 and A3.10
2	The approach to the modelling of future materials /manufacturing emissions is a major simplification as it is based on the decarbonisation of electricity to 2050. This methodological choice will affect mainly the impacts from materials that do not use significant amounts of electricity and so may not decarbonise as quickly due to other emissions sources.	Our methodology for calculating future impacts from most materials only varies the impacts directly due to electricity consumption in the material production chain. Hence, decarbonisation benefits are largest for materials using a lot of electricity process energy, and are relatively low when it is only a small share. Indeed, this is still a simplification, but this should capture some of the future effects in a manageable way. Our project is not aimed primarily at exploring material differences, but rather powertrain/fuel comparisons, and how these might evolve over time. The scope of the work is vast, and as such it was not possible to look in great detail at each element; instead, we had to focus on the areas that would be responsible for the major differences between different powertrains. Since the vast majority of LCA studies make no accounting for improvement /change in material production impacts, this is a marked improvement on these nevertheless.	Main report: 3.2 Appendix: A3.10

#	General question or comment	Response	See section
3	You assume material decarbonisation due to mainly process electricity impacts, but there could be other process improvements/changes that could offer significant further reductions for certain materials (e.g. steel).	As indicated above, due to the broad nature of the study, it was not possible to go into great detail in certain areas, and one of the overall objectives was to provide a consistent and harmonised approach across the study. Assessing the impacts due to improved electricity impacts was an area that could be applied in a consistent way across all materials. Some further process efficiency improvements were also included (based on IEA materials analysis) for steel and aluminium, but it was not possible to conduct a more detailed assessment into broader future potential. We acknowledge that there could be significant further improvements to the processing of key materials, and that the opportunities for different materials are likely to be asymmetric (i.e. some will have greater improvement potential than others). Whilst such an assessment is not the primary focus of this study, it could be a useful topic for a separate dedicated piece of work in the future.	N/A
E	***Electricity production chains***		
1	The impacts from electricity production can vary significantly between member states; your study does not represent this in the overall results. The use of marginal emissions factors would ensure a more balanced comparison, and the results for electric vehicles should reflect the range of electric footprints in national grids.	Our analysis already fully accounts for the variation in electricity generation mix both geographically (where we provide a sensitivity analysis to make very clear the impacts in extreme cases within the EU) and also temporally (where we provide results showing how the impacts vary over time). Since the presentation to stakeholders at the final meeting we have also added a broader set of results in the main report of how the performance of the average conventional ICEV car compares to a BEV operating in each country of the EU (based on the variation in generation mix, different shares of urban/rural/motorway driving, and a limited accounting for average ambient temperature variations). In addition, the generation mixes/electricity production used in the overall vehicle LCA are based on EC modelling of the <u>whole</u> EU energy system (including transport). These mixes therefore already fully account for the overall country and EU-wide changes/increases in demand for electricity in the future based on both increase in electric vehicle uptake (and the demand from these), as well as the multitude of other demands for electricity. In this sense they already represent the average 'marginal' case for electricity. The default EU-average presentation therefore provides a clear and reasonable 'average' case in the EU taking into account increased demand for electricity from all users. We also provide a wide range of other important sensitivities that show how the results for different powertrain types are influenced (in a positive or negative way) by different assumptions or circumstances.	Main report: 4.7 and 5.5.2

#	General question or comment	Response	See section
F	***Fuel production chains***		
1	What is the level of comparability between chains evaluated via an attributional LCA approach vs chains evaluated via a consequential approach?	Some elements of consequential LCA were introduced to evaluate multi-functionality via substitution (in line with ISO 14040) and include impacts from avoided counterfactuals, especially for secondary (i.e. waste/residue based) chains. In turn, primary fossil fuel chains were assessed through an attributional LCA method. Therefore, a direct comparison of these chains was not possible, due to these methodological differences. In order to enhance comparability, the well-to-tank results for fuels used in the vehicle modules are all based on an attributional (incl. energy allocation) approach. The result viewer also allows users to generate results with or without counterfactuals and select an energy allocation or substitution for co-products.	N/A
2	In counterfactual scenarios, the assumption that all feedstock for biofuels needs to be diverted from other existing uses is not always correct, as some residues/waste are reportedly available in large amounts.	The project team agrees with this analysis. Limitations regarding the modelling of counterfactuals are fully acknowledged in the final report and we are indeed aware of the fact the assumption that our approach represents one particular case where that feedstock has an existing use, and does not reflect any other existing use of that feedstock or a situation where it has no existing use. The implementation of counterfactual scenarios was based on recommendations found during the literature review, which were further confirmed during the stakeholder consultation. Ideally, several counterfactual scenarios should have been modelled, taking into account supply elasticities, but the breadth of the study did not allow that. As stated above, the final report and summary result viewer include results with and without counterfactuals and WTT impacts used in the vehicle modules do not include counterfactuals.	Main Report: 5.3.2.3.3
3	The study does not credit the fact that many energy co-products from renewable fuels are dispatchable (and therefore essential to the otherwise assumed decarbonisation of the grid through time). The electricity substituted by biomass residues (e.g. lignin) would rather be marginal natural gas or coal-based production, rather than grind electricity. Is this reflected in the modelling?	The objective, while in line with ISO prescriptions, was primarily to measure the impact of this approach on results, not to generate the most realistic and accurate results. Within the scope of this study it was only possible to consider one substitution scenario for each co-product. In the case of electricity produced as a co-product, it is assumed to substitute an equivalent amount of grid-average electricity, but we recognise that the evaluation of marginal electricity sources should be included in further research. In the case of other energy-containing co-products (e.g. glycerol) they are assumed to substitute an equivalent product in the market. Exploring the additional substitution scenarios is identified as potential future work, but was not possible within scope of this work.	N/A

#	General question or comment	Response	See section
4	What are the data sources for primary biofuels? How representative are those of country specificities or most sustainable cultivation practices? why are the GWP impacts different from other sources, e.g. RED II or JEC WTT?	Data for feedstock cultivation for primary biofuels are extracted from Ecoinvent, with some customisation to replace N_2O emissions with JRC's values (as found in JEC WTT), which are based on GNOC. Also, land-use change emissions are removed because LUC (and SOC) emissions are added separately, based on GLOBIOM. Datasets were selected in Ecoinvent on the basis of their temporal (i.e. recent enough) and geographic representativeness. For most crops (except sugarcane and palm), we picked a dataset from a country representing typical agricultural practices and/or a large share of European production (e.g. France, Germany). Note that in several cases, the same datasets are replicated across several countries; since a lot of agricultural datasets were entered and validated by EMPA, we used a few Swiss datasets too. Data for feedstock conversion into biofuels and transportation are primarily from the (JRC, 2019a), with some supplemental literature and JEC WTT study data used for the production of synthetic fuels from SRC wood. The data used generally reflects an average case for Europe. Further, the background datasets used for production assume, where possible, an average European case. Electricity used in production and transport assume an average European grid (Module 2). The GWP impacts calculated in this study are different to the REDII default values and JEC WTT for a number of reasons, including different methodological choices (e.g. substitution, counterfactual, indirect land-use change etc.). The effects of these choices are explored in the main report.	Appendix: A3.12.2
5	Aside from the GLOBIOM values, did you try to model different economic conditions, different GWP amortization periods or use different LUC models?	The breadth of the study did not allow to implement variations in the LUC factors used for the calculation of the cultivation impacts. Following the stakeholder consultation, figures from GLOBIOM were used, which happen to be based on a 20-year amortization period. The objective was to assess the impact of including LUC emissions (incl. SOC) on results, taking into account crop specificities (which is not the case in RED II, which averages values per crop categories). Results can be modelled with or without LUC values and these limitations are clearly stated in the final report. We are aware that the modelling of economic shocks in the initial GLOBIOM studies are based on a set of data and assumptions, which may have changed, especially with the new conditions (e.g. caps and subtargets) in RED II, but modelling those were not part of the scope of this study.	Main report: 5.3.2.4
6	How did you model ethanol blends above 10% (legal limit)?	Future blends above 10% are modelled using advanced drop-in synthetic fuels, most of which are based on waste or residues (no LUC emissions applied).	Main report: 4.7.4

#	General question or comment	Response	See section
7	Why do certain MSW-based or biomethane chains result in higher GHG emissions than in other studies?	In this study we investigated several new methodologies, which have had an impact on results: - For feedstocks which are wastes, we investigated the impact of diverting that feedstock from another existing use to fuel production. If it is already used e.g. for power generation, then we examined what the impacts of supplying that power by an alternative means would be. These are termed ‘counterfactual emissions’. For agricultural residues, forest residues, and sawdust the counterfactual emissions are quite large as a scenario was examined where these feedstocks are already used for power production, and hence that power must be provided by another means. For manure-derived SNG the counterfactual emissions are negative as using the manure for AD avoids some methane leakage from manure storage. - We investigated the use of a substitution approach to co-products which can cause the results from our study to look quite different to the typical energy allocation approach that is used in RED. - MSW-based chains do include a share of fossil feedstock (we didn’t model the biogenic and non-biogenic fractions of MSW), which is why additional fossil emissions are accounted for. In addition, the overall efficiency is fairly low, which tends to amplify these high GHG emissions and the avoided electricity production from waste incineration is compensated by additional electricity being produced from the grid. In the Result Viewer accompanying this report, MSW chains can however be modelled without counterfactual emissions and using an energy allocation to address multifunctionality.	Appendices: A3.6.3
8	What source of electricity is used for e-fuels?	All hydrogen and e-fuel chains were comparatively modelled with grid electricity and 100% renewable electricity to assess the impact of electricity sources on results. Results are included in the final report.	Main report: 5.3.2.5
9	What sources of natural gas are used for CNG, LNG and SMR-H_2? Is a fraction of biomethane included in the mix? Has the injection of H_2 in the gas network been considered?	The modelling of natural gas chains is based on an average EU mix of natural gas and downstream processes. Future gas blends take into account the increasing share of biomethane and renewable gas in the natural gas mix. The injection of hydrogen in natural gas network was, however, not modelled in this study. The emission factors used in this study were based on the Environmental Footprint (EF) 2.0, as modelled in Ecoinvent, following the agreed LCIA impact categories.	Main report: 3.4.2.1.2

#	General question or comment	Response	See section
10	Why is Bio-LPG not modelled?	A large number (60) of fuel chains were modelled in this study, but the breadth of the study did not allow for each and every liquid or gaseous fuel to be modelled. Therefore, it was only possible to include two routes to LPG: LPG produced from conventional crude oil and LPG produced from unconventional crude oil. In the final results viewer it is possible to examine differing blends of these two LPG sources over time.	N/A
S	***Vehicle specification***		
1	Why have BEV, FCEV, FC-REEV powertrains been modelled for articulated lorries if these solutions are not currently available on the market and are not expected to be widely available? A 500 km range for a BEV or FCEV artic lorry is not possible in 2020.	Key objectives for this project included providing a harmonised and consistent comparison of current and potential future powertrain options for road vehicles, in order to inform policy-makers and other stakeholders on the potential strengths and limitations of different options. With the policy focus, the assessment deals with generic vehicles, rather than real-specific models (also a necessity given the time horizon for the analysis looking out to 2050). Whilst certain specific powertrain options do not currently exist for certain vehicle categories, it was important to still include these to help assess their potential attractiveness. A number of manufacturers also have BEV, FCEV and FC-REEV models under development (e.g. Tesla, Toyota, and Nicola), with ranges at or above 500km proposed. Assessing what the potential implications for the environmental impacts of such models would be was therefore deemed useful (and necessary) and an assessment as to what could be a feasible (usable) was made based on this, and Ricardo's previous analysis on future ZE (zero-emission) HGVs for the UK Committee on Climate Change (Ricardo Energy & Environment, 2019).	N/A

#	General question or comment	Response	See section
2	You assume a lower medium card doing 225 000 km over 15 years with one single battery. However, car EV batteries are generally only warrantied for 8 years and 100,000 km - this therefore seems too optimistic? You assume a lifetime activity of 800 000 km for an articulated lorry, which seems short when considering EU average age of HDV of 12 years (ACEA)? This could impact on the battery's duration in the vehicle and potential need for replacement.	The assumed vehicle lifetime's and lifetime mileage assumptions for different vehicle types are based on previous detailed analyses for the European Commission, which are summarised both in the main report and in the more detailed Appendices. Both light- and heavy-duty vehicles have higher annual mileage at the start of their lifetimes, which on average decreases over their lifetime; for large lorries, these tend to be shifted across from longer-haul or regional delivery operations onto shorter duty cycles in later years. This is also partly due to lower reliability and higher fuel costs (compared to newer models) in later year, and the largest (articulated) lorries tend to have a lifetime of around 10 years (with smaller lorries having a longer life in years, but lower lifetime km). This is factored also into our analyses. Battery warranties are based on a range of considerations including (but not limited to) a vehicle/battery manufacturer's conservative estimate on what level of warranty would give sufficient confidence to new vehicle buyers, whilst also minimising the risk of significant battery returns, even when vehicles/batteries are used in more extreme (or unknown) conditions. They do not represent the manufacturers expectation for the average lifetime of batteries in their vehicles, and Ricardo's discussions with OEMs (and the views of our own battery experts) indicate that in most cases the batteries used in light-duty vehicles should be now be expected to as the life of the vehicle, except in extreme conditions/usage. In our study, the methodology used to determine the need for battery replacement takes into account the lifetime energy requirement for the vehicle, the available battery capacity and the anticipated cycle life of the battery. This methodology was agreed with stakeholders, and similar approaches are also being proposed/applied in other EU initiatives, such as in the development of specifications for battery eco-design and PEF (product environmental footprint). As higher capacity batteries are included in newer xEV models, so fewer charge/discharge cycles are needed to supply the required energy over the vehicle's lifetime. In addition, the cycle life of newer batteries is being improved through a combination of improved chemistries and better battery management and thermal solutions.	Appendix: A3.13.3.3 and A3.13.3.4

#	General question or comment	Response	See section
3	Why has the utility factor of a PHEV been set at 75% when it has been shown that in practice it could be much lower given recharging behaviour?	The utility factor used for light-duty vehicles is based on that defined under WLTP (the world harmonised light-duty test protocol) used for regulatory testing / type approval in the EU, and has been defined to represent an average case. Since the draft results presented at the project workshop, we have amended the calculations to use this utility function together with a real-world estimate for electric range to further refine the result. Nevertheless, the actual charging behaviour and driving practices of PHEV owners in the real-world can have a big impact on the overall result, so sensitivities are also presented in the main report for cases where the electric driving share is much higher, or much lower. At the possible two extremes (i.e. only driving in electric mode, and never charging up the vehicle) the results will tend towards a similar result as for a BEV or a regular HEV vehicle.	Main report: 5.5.4
O	***Overall vehicle LCA***		
1	Why has this study not included a sensitivity explicitly modelling different locations of battery production?	Our default battery manufacturing analysis factors in the current market mix of production of xEV batteries (i.e. with most of the production currently in China, Korea, Japan and the US), and future projections for how this mix may change with more localised production in the EU. Our study already includes a range of sensitivities on batteries, including: a sensitivity on a more EU-focused production, to help illustrate the impacts of this, as well as sensitivities on the improvements in battery energy density/ technology. Following the final meeting we have also provided a sensitivity on the specific outputs of the battery manufacturing calculations showing the variation in results for different manufacturing energy assumptions and for manufacturing in the EU versus China. We feel the combination of these sensitivities provides an appropriately wide exploration of the potential variation of the outcomes based on different situations and assumptions.	Main report: 5.5.11, 5.5.12, and 5.5.15

#	General question or comment	Response	See section
2	Why has this study not included a sensitivity modelling alternative end-of-life approaches? Why is the use of a more complex approach appropriate for policymaking?	The end-of-life methodology was a topic of considerable debate during the stakeholder consultation, and we acknowledge that some stakeholders prefer alternative approaches. However, most of the LCA expert stakeholders we consulted preferred the use of approaches taking into account both recycled content and end-of-life recycling rates in a hybrid approach. The PEF methodology has been developed for the Commission to help facilitate the reduction of the environmental impacts of goods and services taking into account supply chain activities, and the PEF Circular Footprint Formula (PEF CFF) has been developed to provide a more sophisticated accounting for end-of-life impacts, and is aligned with the results of our consultation and the objectives of this study. This approach was therefore selected to be implemented in our study. This study is extremely broad, and whilst we have attempted to provide sensitivities for a range of uncertainties / situational considerations, it has not been feasible to include all possible variations. Therefore a sensitivity on the end-of-life methodology has not been implemented in this study. However, further assessment of the implications might be considered in future work.	N/A
3	Why are the end-of-life impacts similar for all powertrains if recycling of batteries is uncertain?	There are already requirements for recycling of vehicles and xEV batteries under existing EU legislation, including the Batteries Directive. These instruments are currently also under review with the objective of maximising the technically achievable recycling and recovery rates, and there are many activities being conducted at an EU and international level on improving battery recycling and recovery rates. In this context, the uncertainty with regards to future recycling of xEV batteries is not on whether this will happen/be required (it is/will), but rather on the level of material recovery/efficiency and economics of future activities, and the extent to which such activities (and the recovered resources) can be largely retained within Europe. Our analysis takes these considerations into account and utilises the best available information/data on the current and potential future performance of vehicle and battery recycling processes to estimate impacts. The calculated net end-of-life impacts for different powertrains actually varies quite significantly, however the net impacts are smaller in absolute terms in comparison to the impacts from manufacturing and operation. This is in part due to a combination of emissions impacts resulting from end-of-life processing activities and recycling (/battery 2nd life) credits.	Appendices: A3.8, A3.13.4, and A4.3.4

#	General question or comment	Response	See section
4	Conclusions on gas-fuelled vehicles are based on outdated assumptions regarding methane split of dual-fuel powertrains	We have amended (reduced) the methane slip assumptions for HDVs based on the recently published Cenex work that was identified only after the final meeting (Cenex, 2019).	Main report: 5.4.2.1
5	NMVOC emissions from gas-fuelled vehicles appear to be much higher than what would be expected	We identified an issue with NMVOC where data based on COPERT speed-emission curve calculations were used unchanged, but included all VOC (i.e. also methane). The methane component has been subsequently removed from the calculations for our final analysis/this report.	N/A
6	Assumptions concerning future electricity mixes (e.g. increase in the use of electricity from wind, large share of renewables in 2050) and fuel mixes (e.g. share of total non-fossil sources in CNG/LNG mix in 2020 and 2030) are unrealistic.	All assumptions regarding future electricity mixes and fuel mixes are based on two European Commission modelling scenarios (Baseline, Tech1.5) from the analysis for the Long Term Strategy for 2050 (European Commission, 2019). This methodology was discussed and agreed with stakeholders during the consultation during the project.	Main report: 4.7.1 Appendix: A3.11

A3 Appendix 3: Detailed overview of the developed LCA methodology

This appendix provides a more detailed summary of the methodology developed and applied in this project.

A3.1 Overview

The basic framework for developing the LCA methodology under this study has been derived through the following process:

- Extensive literature review covering 347 sources
- Two rounds of stakeholder Delphi survey (see Appendix A2)
- Stakeholder workshop in Brussels on February 25th, 2019 and subsequent feedback
- Final stakeholder meeting in Brussels on January 16th, 2020 and subsequent feedback.

The overall methodological choices based on this process and further background information are documented and justified in detail in the following sections. Table A7 gives a summary of key aspects of the final methodological framework.

Table A7: Basic methodological framework for the LCA study

Issue	Approach used in LCA study	Appendix Section
Goal	Enhance the understanding of life-cycle impacts of transport vehicles on a quantitative basis and create a basis for comparing various vehicle/fuel combinations.	Section A3.2
Product system(s)	Six different types of road vehicles (light and heavy duty) with twelve different powertrain options are analysed (in total 50 combinations). Furthermore different fuel and electricity chains potentially applicable to the analysed vehicles are included in the analysis.	Section A3.3
Functional unit and reference flows	Technical comparisons of vehicles similar in size and utility, which are defined by the vehicle type, size class (e.g. GVW) and potentially segment (for passenger cars). Vehicle kilometre and vehicle-life are the main reference flow for life-cycle results, additional units are used for interim results.	Section A3.5
System boundaries	Whole life cycle of the vehicles themselves, from manufacturing and fuel/electricity production to the use phase (including maintenance) and the end-of-life. Additionally infrastructure for energy production (electricity and fuels) is included.	Section A3.6
LCA approaches	Overall a consistent attributional approach is applied. For fuel chains elements of consequential LCA were introduced to evaluate the impact of diverting secondary feedstocks from its counterfactual use to fuel production.	Section A3.7
End-of-life modelling	Application of the PEF ‘Circular Footprint Formula’ (CFF), which represents a more sophisticated hybrid approach combining aspects of cut-off and avoided burden approach, as well as accounting for material quality and allocation between the material supplier and recycler. In practice a cut-off approach is effectively resulting for many materials where there is an even balance between use of secondary material and recycling rate, nor quality considerations. An additional credit is given for selected materials where the recycling rate significantly exceeds the content of secondary material.	Section A3.5

Issue	Approach used in LCA study	Appendix Section
Impact categories	Commonly established midpoint indicators including greenhouse gas emissions, acidification, eutrophication, summer smog, ozone depletion, ionising radiation, particulate matter formation, human toxicity, eco-toxicity, resource depletion, land use and water scarcity.	Section A3.9
LCI background data	For the background system ecoinvent is used as a transparent and established data base. Where the quality of the original Ecoinvent datasets was not sufficient, data from other sources is used.	Section A3.10
Foreground data: electricity production	Electricity module based on existing ifeu model including upstream fuel chains, power plant processes, distribution of electricity and production of capital goods for the major generation types (hard coal, brown coal (lignite), fuel oil, natural and derived gases, biomass (solid and biogas), nuclear, solar, hydro and wind power). EU electricity conversion efficiency, generation mix, losses and imports/exports from EC energy modelling outputs. Non-EU electricity generation mix based on IEA projections for key global regions.	Section A3.11
Foreground data: fuel production	Due to the large number and diversity of feedstocks and fuels covered, a combination of datasets from different sources was required. No single publicly available dataset includes full lifecycle inputs and outputs for the 59 fuel chains modelled in this study. Most conventional fossil and biofuels are well documented in LCA datasets and other mainstream studies. Land-use change, soil organic carbon (SOC) emissions and N_2O emissions were included for primary biogenic fuels, and counterfactual impacts for fuels produced from secondary feedstocks were assessed. For less commercially mature fuels, e.g. synthetic fuels, secondary fossil fuels or e-fuels, data was not as readily available. In some instances, single peer-reviewed publications for a lifecycle stage were combined with other datasets for lifecycle stages. All assumptions used to combine datasets from different sources have been documented in the model.	Section A3.12
Foreground data: Vehicle specification	High-quality sources used to characterise vehicles and powertrains. Datasets based on market average input data used to define reference vehicle powertrains and average vehicle lifetime/activity, together with recent studies for the EC. Modular component-based approach use for powertrain specification using datasets based on existing high-quality sources, with key assumptions validated with Ricardo experts and external expert stakeholders. Detailed assumptions used to define battery sizing /performance and the variation in operational energy consumption of vehicles. Operational pollutant emissions based on inventory-based methodologies. Sensitivities defined for all the most influential parameters.	Section A3.13
Foreground data: Vehicle cycle	Vehicle manufacturing based on material use in vehicles/components, generic manufacturing loss factors, and assumptions on recycled content. Detailed specific characterisation of battery manufacturing and end-of-life based predominantly on data/methodologies applied in the GREET life-cycle model. Maintenance based on replacement components/consumables. Spatial and temporal considerations applied to account for regional shares of manufacturing of vehicles and batteries (separately). End-of-life treatment impacts/credits as indicated above.	Section A3.13

A3.2 Goal

"The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated." (ISO14040, 2006)

A3.2.1 Policy context

As set out in the 2016 Commission Communication on the European Strategy for Low-Emission Mobility and, more recently, the 2018 Commission Communication on a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, the decarbonisation of transport is pivotal to achieve a climate-neutral Europe by 2050.

This can only be achieved with a range of instruments, including the following, which have already been implemented in the EU:

- Binding annual greenhouse gas (GHG) emission targets for Member States for the periods 2013–2020 and 2021–2030 covering emissions from sectors not included in the EU Emissions Trading System (EU ETS), such as transport, buildings, agriculture and waste.
- CO_2 fleet targets for tailpipe CO_2 emissions of new cars and vans.
- Fuel Quality Directive and Renewable Energy Directive targeting GHG emissions from the production of transport fuels.
- The EU ETS, which covers GHG emissions from the production of fuels and electricity. This also partly covers the manufacturing of vehicles and the production of the raw materials used therein.

Road transport has also been identified as one of the main sources of air pollution affecting both human health and the environment. Air quality standards in relation to NO_x and particulate matter (PM) are still exceeded in the EU. Tailpipe emissions of these pollutants are targeted mainly by EU emission standards for passenger cars and vans (currently Euro 6) and heavy duty vehicles (currently Euro VI).

There also exist further policies which address certain life-cycle stages or vehicle components such as batteries, waste, energy efficiency, pollution prevention and control and the end-of-life of vehicles.

Most of the current policy instruments focus on specific aspects of vehicle life-cycles and target a limited range of environmental impacts. A full picture of all the 'most relevant' impacts over the full life-cycle of vehicles is therefore desirable, in particular as road transport increasingly moves towards alternative fuels and powertrains. While, traditionally, the use phase has accounted for the most significant proportion of overall vehicle lifecycle impact, other life-cycle stages (i.e. energy generation and vehicle production) are dominating impacts for alternative fuels and powertrains. Other types of environmental impacts may also become more relevant with this shift.

To inform future policymaking, it is therefore becoming more important to develop a better understanding of the environmental impacts of road vehicles over their entire lifecycle and across a range of potential environmental impacts. Life cycle assessment (LCA) is a tool to reveal possible trade-offs between environmental impacts in different life cycle phases, as well as between different impact categories. This is particularly important to enable the appraisal of different vehicle fuels and technologies on a comparable basis. An LCA can help to identify environmental hotspots/key impacts throughout the different life cycle stages, in order to better understand opportunities to reduce them, as well as mitigate any potential burden shifting between life cycle stages.

A3.2.2 Goal of the study

The goal of the study was explicitly stated in the technical specifications:

"*The aim of this study is to look into the environmental impact of road vehicles in a holistic manner, using a life-cycle assessment (LCA) approach covering the manufacturing, use and end-of-life phases of the vehicles, taking into account the fuels used. It is meant to enhance the Commission's understanding of such impacts and the methodologies to assess them in view of the further development of climate change, energy, air quality, and transport related policies for the mid- to long-term time frame (2020 to 2050).*"

To answer these questions the study follows a two-step approach:

1) The development of an LCA methodology. The applied approach is documented in this section.
2) The subsequent application of the LCA methodology to explore quantitatively how different vehicle types (combinations of powertrains and fuel types) compare to each other in terms of GHG emissions and other main environmental impacts and how this will evolve between 2020 and 2050. The latter requires that the impact of existing and future policies is taken into account.

Since the goal of the study falls into the area of policy application, with the key objective to enhance the Commission's understanding of the complex impacts of road transport vehicles on a quantitative basis, the intended audience is foremost the European Commission and associated policymakers. Future updates and developments, however, may have different target audiences. The broad stakeholder consultation within the project broadens the target audience for (interim) results further.

IMPORTANT NOTE: The goal of this study was not to assess or develop methodologies for reporting the life cycle CO_2 emissions of *all* new vehicles as the Commission is requested to do under the LDV and HDV CO_2 Regulations, rather the goal was to inform policy-making. Elements of the methodologies and key datasets utilised in this study would therefore need to be adjusted for a regulatory/product LCA purpose. Further considerations on this can be found in Appendix A6.

A3.3 Criteria and basis for methodology development

The following key criteria have been defined to guide the appropriate methodological choices in this study:

- **Compliance with goal and scope**: Suitability to inform policy making.
- **Relevance of overall expected impact**: Elements expected to exert high societal impacts require more detailed consideration and finer analysis, e.g. as part of sensitivity analysis.
- **Appropriateness for the object of investigation**: The objects of investigation are road transport vehicles and the methodology should cover the key impacts currently associated with road transport and its upstream processes.
- **Transparency**: Transparency is important especially in the context of democratic, science-informed policy making open to public scrutiny. This concerns transparency of underlying data as well as methodological transparency.
- **Suitability for spatial and temporal differentiation**: Spatial and temporal differentiation is a clear goal of the study and of importance to inform policy making on an EU level. The methodology thus needs to allow for scenario building by e.g. varying key parameters.
- **Balancing available resources for application:** The scope of the assessment is very broad – i.e. covering a range of different vehicle types, fuels and electricity chains, and looking out to 2050. The developed methodology therefore also needs to reflect the available resources for this 18-month study, e.g. full vehicle simulation is not feasible, and attention is necessarily focussed on the most important options and impact types.

For the methodological choices, several commonly used guidelines for LCA were identified in the literature review and are used as a main reference for methodology development:

- The **ISO 14040/144044** (ISO14040, 2006) (ISO14044, 2006) norms provide the common basis for all LCA studies today in the form of a standard. They include general requirements for all aspects of a products lifecycle. ISO 14040/144044 have been identified as the key methodological basis in this project. However, the ISO norms still leave many methodological aspects to be further defined by the LCA practitioner. Therefore further guidelines have been taken into account.
- The **ILCD handbook** (JRC, 2010) was written by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in co-operation with the Environment DG in 2010. It is in line with the ISO standards and consists of several documents: a general guide on lifecycle assessment, a specific guide on lifecycle inventory, a guideline on lifecycle impact assessment methods (including a set of recommended LCIA methods) and a guide on review criteria.

- The **Product Environmental Footprint (PEF) Guide** (JRC, 2012) provides a harmonised European methodology for Environmental Footprint (EF) studies using a life-cycle approach. This very general guidance document is scheduled to be complimented by more specific Product Category Rules following the PEFCR guidance (JRC, 2018a). One such Product Category Rule is the **PEFCR for batteries** (RECHARGE, 2018) which provides detailed and comprehensive technical guidance on how to conduct a PEF study for rechargeable batteries.

Other guidelines give provisions for specific aspects or life-cycle phases of the vehicle LCA and have been consulted in respect to certain aspects. Out of those the **eLCAr guidelines** for electro mobility (eLCAr, 2013) and the **FC-Hy Guide** for hydrogen (FC-Hy, 2011) have been analysed. The eLCAr guidelines provide guidance for the LCA of electric vehicles and are based on the ILCD handbook. The idea was to create a common framework concerning methodological choices and assumptions for electric vehicles and enhance the comparability of studies conducted in this field. The FC-Hy Guide has a similar scope. It provides a detailed technical guidance on how to conduct LCAs for fuel cells (FCs) and hydrogen production systems and is also based on the ILCD handbook. 26 out 34 participants in the Delphi survey (strongly) agreed that the above mentioned are the most important guidelines for consideration.

The methodological scope for this study has been developed as a decision making process based on these guidelines and criteria and reflected by the stakeholders. The methodological choices are documented and motivated in detail in the following sections.

A3.4 Product system(s) (and functions)

A3.4.1 Product system(s) for vehicles

Product systems on the vehicle side are defined by a vehicle type and power train combination.

The following vehicle types are distinguished:

- Passenger car (M1 vehicles), broken down into two sub-segments, i.e. lower medium and large sports utility (SUV) segment.
- Van, i.e. Light Commercial Vehicle (LCV) (N1 vehicles).
- Rigid lorry (N2 or N3 vehicles).
- Articulated lorry (tractor + trailer) (N3 vehicles with typically 40/44 tonnes GVW).
- Urban bus (M3 vehicle, low floor - Class II).
- Coach (i.e. long distance or intercity bus, M3 vehicle, high-floor - Class III).

Even though there are differences in the vehicle body/glider architecture for certain alternative powertrain vehicles (notably BEVs), the literature review and previous experience/analysis suggested that these differences are unlikely to be particularly significant to the overall result in comparison with other considerations (i.e. the powertrain-specific components, and particularly the battery specification).

The general body types are combined with the following powertrain options:

- Gasoline internal combustion engine vehicles (ICEV)
- Diesel ICEV
- Compressed natural gas (CNG) ICEV
- Liquefied petroleum gas (LPG) ICEV
- Liquefied natural gas (LNG) ICEV
- Gasoline hybrid electric vehicle (HEV)
- Diesel HEV
- Gasoline plug in hybrid vehicle (PHEV) / range extended electric vehicle (REEV)[42]
- Diesel PHEV/REEV[42]
- Battery electric vehicle (BEV)
- Fuel cell electric vehicle (FCEV)
- HEV/BEV-ERS (Electric Road Systems)[43]

[42] REEVs usually somewhat differ from PHEV and tend to have a serial hybrid configuration in which their internal combustion engine has no direct link to the wheels, but is used as a generator only. The conventional engine is thus often smaller and the battery larger in comparison with a PHEV. Since both vehicles are nevertheless similar in their component composition, the difference is assumed to be rather in terms of vehicle specification.

[43] An Electric Road Systems (ERS) truck is powered by an electric drive system in which propulsion electricity is drawn directly from a network while driving. ERS thus largely circumvent the technical limitations of electric mobility, including those associated with the battery storage system (energy density, charging power, weight). Though there are several technical solutions for electrification, overhead catenary lines are probably the most

- Fuel cell range-extended electric vehicle (FC REEV)

Since not all power trains are equally suited and common for the vehicle types, the theoretical number of 72 combinations of vehicle type and power train can be narrowed down to 49 combinations as shown in Table A8 which are considered realistic and mostly are available. Each of the vehicle types and power train combinations is specified from a technical perspective. This technical specification then is reflected in the modelling of the production process.

Generally, the vehicle type and power train combination and its technical specification are largely fixed over the entire life-cycle. The combination also defines technically which type of fuel can be used in the vehicle, and hence the fuel chains which must be modelled. Nevertheless, energy production/ electricity generation is to a large extent independent from the product system of the vehicle. Energy chains and associated impacts are also subject to changes over the life-time of a vehicle and vary by geographical use. The coverage of product systems for liquid and gaseous fuels as well as electricity generation is therefore discussed separately in the following sections.

Table A8: Summary of vehicle/class and powertrain combinations

Body type:	Passenger car	Van	Rigid lorry	Artic lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV*	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck	Typical SD, 24 t GVW
Gasoline ICEV	Y	Y				
Diesel ICEV	Y	Y	Y	Y	Y	Y
CNG ICEV	Y	Y	Y	Y	Y	Y
CNGL ICEV			Y		Y	Y
LPG ICEV	Y	Y				
LNG ICEV			Y	Y	Y	Y
LNGD ICEV			Y	Y		Y
Gasoline HEV	Y	Y				
Diesel HEV	Y	Y	Y	Y	Y	Y
Gasoline PHEV	Y	Y				
Diesel PHEV	Y	Y	Y	Y	Y	Y
BEV	Y	Y	Y	Y	Y	Y
FCEV	Y	Y	Y	Y	Y	Y
FC-REEV			Y	Y		Y
Diesel HEV-ERS				Y		
BEV-ERS				Y	Y**	

Note: * Based on EU registrations-weighted averages for: Lower Medium = defined as segment C vehicles (e.g. VW Golf) <u>and</u> medium SUVs (e.g. Nissan Qashqai); Large SUV = Large SUVs / Crossovers (e.g. BMW X5, Land Rover Range Rover, Volkswagen Touareg, Volvo XC90, etc.). **Urban bus using regular ultra-rapid charging via a pantograph connection at stops along its route, enabling a significantly smaller on-board battery. Not a trolleybus. *** CNGL = CNG lean-burn engine; LNGD = dual-fuel LNG-Diesel HPDI engine.

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common option currently since this technology is known and proven in the rail sector. Overhead catenary trucks are usually hybrids in order to cover road stretches without electrification. Two common options for vehicles using ERS are diesel-electric hybrids, where the diesel engine allows for hybrid driving on non-electrified road stretches, and battery-electric hybrids, where an on-board battery allows for a certain driving range (though much smaller than for a regular BEV) on non-electrified stretches. However, fuel cell electric options might also be a possibility. Though there are several technical solutions and technology is still developing, articulated lorries using ERS are considered in this study as battery-electric trucks.

A3.4.2 Product system(s) for electricity generation

The scope of the electricity generation product system comprises all relevant (in accordance with the applied cut-off criteria set out in Section A3.6.2) generation technologies on the basis of their share on gross electricity consumption (consumption mix) within the spatial (countries under) scope. The mix is thus adjusted for external trade with third party countries (e.g. Switzerland or Norway). For countries outside of scope, data sets from well-established databases were utilized. The following generation technologies are considered:

- Coal (lignite, hard coal)
- Oil-fired
- Nuclear
- Solar (photovoltaic)
- Hydro
- Natural gas (and derivatives)
- Waste incineration
- Wind (onshore and off-shore)
- Biomass (solid and biogas)

The above describes the status-quo in the EU28 as of 2019 and, dependent on the scenarios applied, could be subject to change over time, as new technologies emerge, or specific technologies are phased out due to political, economic or environmental reasons.

In addition, variation in electricity transmission and distribution losses will be accounted for based on different country conditions.

A3.4.3 Product system(s) for liquid and gaseous fuels

A3.4.3.1 Product system(s)

The scope of the product system covers liquid and gaseous fuels projected to be used in the vehicles defined in Section A3.4.1 in the period up to 2050. Table A9 shows the correspondence between the vehicle types described in Section A3.4.1 and the different types of liquid and gaseous fuels included in the product system. BEVs and BEV-ERS which only require electricity as a 'fuel' are not included in the table. Across the EU and globally, these fuels have a variable share of the current transport fuel mix, and these shares will change in the period to 2050.

Table A9: Correspondence between vehicle types and compatible fuel types

	Vehicle and Powertrain Type							
	ICEV					HEV/PHEV/REEV		FCEV
	Gasoline	Diesel	CNG	LPG	LNG	Gasoline	Diesel	Hydrogen
Gasoline*	X					X		
Diesel*		X					X	
CNG			X					
LPG				X				
LNG					X			
Synthetic Natural Gas (SNG)*			X		X			
Bioethanol	X					X		
Fatty Acid Methyl-Esters (FAME)		X					X	
Hydrotreated Vegetable Oil (HVO)		X					X	
Biomethane			X		X			
Hydrogen*								X

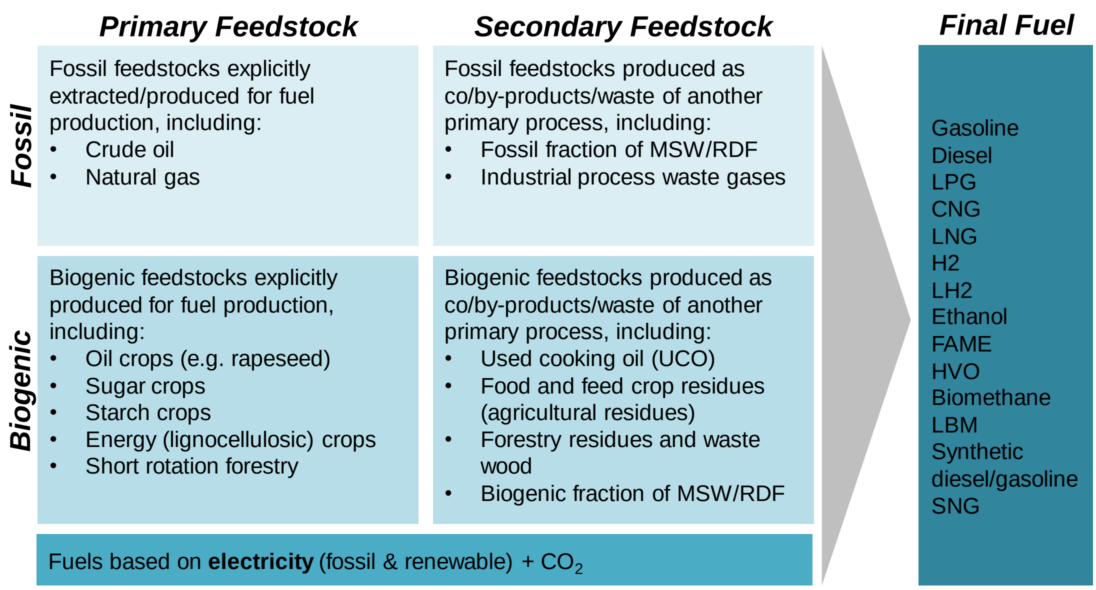
Note: * May be derived from crude oil refining, or synthetic from natural gas, renewables (i.e. power-to-gas/liquid) and/or bio-based (e.g. biomass-to-liquid, BtL).

The fuels included in the above table may be produced through various pathways using a wide range of fossil, renewable and biogenic feedstocks. Five different fuel categories have been defined for this study, based on the characteristics of the feedstock. Figure A33 describes these five categories, namely:

1) Primary fossil fuels;
2) Secondary fossil fuels;
3) Primary biofuels;
4) Secondary biofuels;
5) e-fuels.

Raw materials purposefully extracted/produced (as main product) are called “primary”, whereas raw materials generated as by-product (residues) from other chains are called “secondary”. The fifth category comprises fuels produced by using electricity (e-fuels) to produce hydrogen and gas/liquid derivatives such as synthetic diesel. When entirely produced out of renewable electricity other than biomass (e.g. solar, wind, hydro), these synthetic fuels are often referred to as Renewable Fuels from non-Biological Origin (RFNBOs). The production pathways for each of the fuels are at varying levels of commercial readiness, ranging from the initial stage of commercialisation to full commercial maturity.

Figure A33: Fuel categories (based on feedstock types)



Generally, the fuel supply chains consist of:

- An **extraction/production phase**, during which the raw material is extracted (e.g. crude oil or natural gas), cultivated and harvested (e.g. starch/sugar crop, oil crops and energy crops) and/or collected (waste, industrial residues, agricultural/forestry residues). In some cases, these feedstocks require pre-treatment, often in the form of drying which occurs at the harvesting/production site, prior to the processing and refining stages.
- One or several **processing and refining phase(s)**, where the raw material is transformed into chemical intermediaries and//or final fuel. Where applicable, compression or liquefaction of fuels is included within the processing and refining phases.
- **Transport/storage phase(s)**, which include all upstream, downstream and intermediary transport, storage and distribution phases of the feedstock, intermediates and final fuel. Table A10 provides a high-level description of the end-fuels covered in this study.

The scope of the LCA was consistent for all primary feedstock-derived fuels, with all life-cycle steps of the fuel being included from raw material extraction to the vehicle tank (well-to-tank). For secondary feedstock-derived fuels the life-cycle steps begin at collection of the feedstock and impacts from diverting the feedstock from an existing use (counterfactual impacts) are explored. While most life-cycle impacts of fuels were evaluated on an attributional basis (see Section A3.1), some elements of consequential LCAs were used to evaluate specific impacts, as in the case of secondary (fossil or biogenic) fuels, where feedstock diversion to fuel production may create knock-on (market) effects.

Table A10: Descriptions of end-fuels covered in this study

Fuel/Feedstock	
Diesel/ Gasoline	Co-products from oil refining.
LPG	LPG is a co-product from oil refining, which contains variable amounts of butane and propane and smaller fractions of other hydrocarbons.
CNG	Natural Gas is mostly composed of methane, with smaller fractions of alkanes, CO_2 and H_2S.
LNG	Liquefied Natural Gas.
Synthetic Diesel /Gasoline	Synthetic fuels are obtained through the upgrading of syngas, followed by a Fischer-Tropsch reaction or other catalytic processes. Syngas is composed of carbon monoxide and hydrogen, and is obtained through steam methane reforming (SMR) or coal/biomass gasification.
FAME	Fatty acid methyl ester (FAME) is obtained through the transesterification of vegetable oil, used cooking oil or animal fats. Also known as biodiesel, it is generally blended with diesel at variable rates (from 5 to 20% for most diesel engines).
HVO	Hydrotreated vegetable oil (HVO) is derived from the same feedstock as FAME, but undergoes hydrotreatment, which removes all oxygen from carbon chains and produces a drop-in fuel, which can be used at up to 100% in diesel engines.
Biomethane	Biomethane is obtained through the upgrading of biogas to remove CO_2 and other impurities. Biogas is obtained through the anaerobic digestion of biomass, manure, the biological fraction of waste, and sewage sludge among others.
SNG	SNG is a gas with a similar composition as natural gas, which is obtained through the gasification of coal, lignin, biomass or by combining H_2 and CO_2. In this study, SNG is produced from either biomass or CO_2 and H_2.
e-fuel	Synthetic fuel, for which the energy content comes from electricity (e.g. hydrogen from electrolysis). CO_2, which has no energy content, can be used to provide the carbon content of the fuel. When e-fuels are produced from renewable power source such as hydro, wind or solar power, they are considered as RFNBOs.

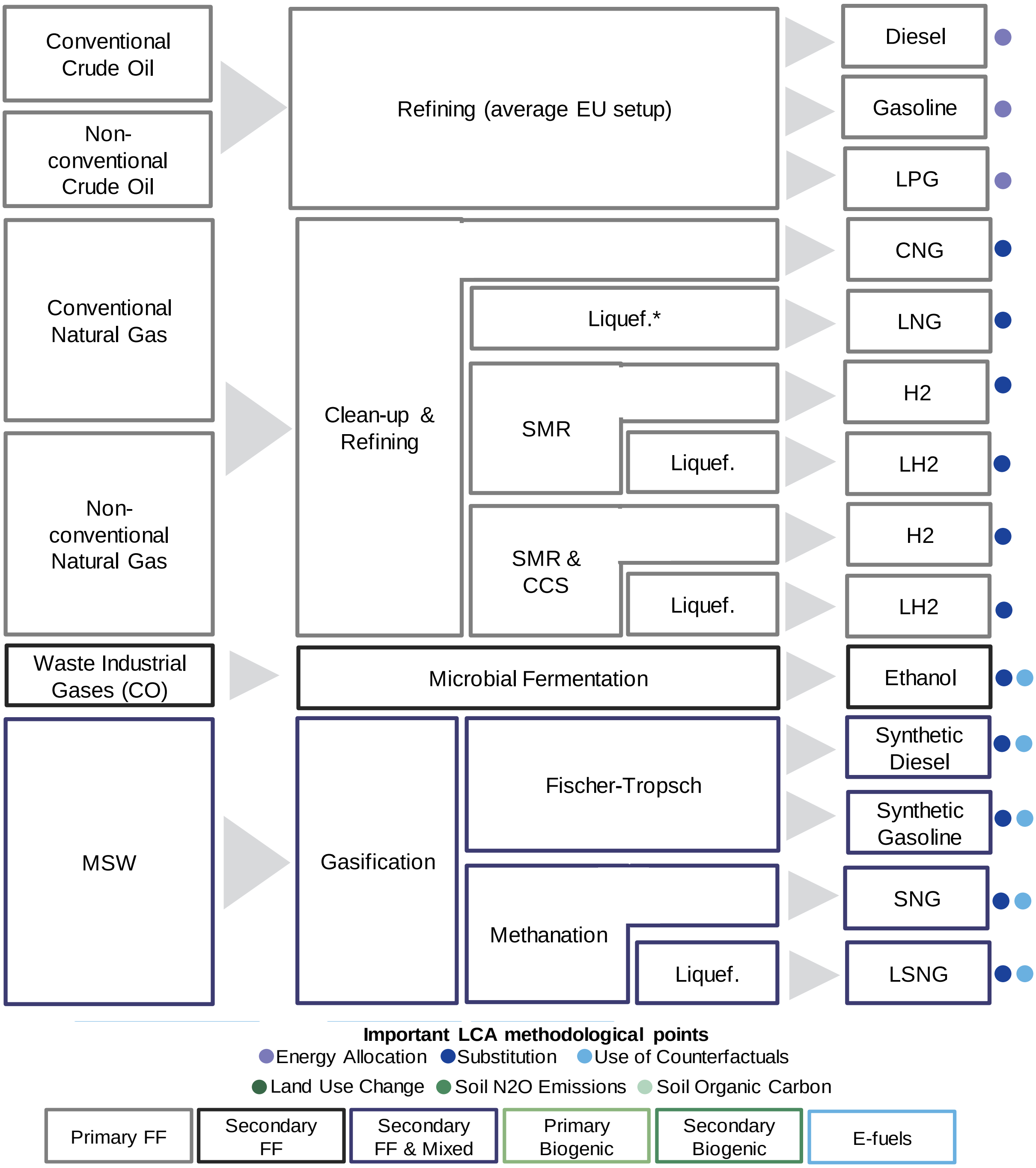
Figure A34 sets out the 60 fuel chains covered in this study, illustrating the feedstock, the key processing steps and the end fuel. These chains were chosen to ensure a good coverage across the different feedstock types, and end fuels which are either prominent in the current and short-term future fuel mix or are likely to be seen in the fuel mix by 2050. For the chains in the latter category, the limited availability of some of the data required to model chains adequately in the LCA must be considered in the results, particularly for those where the production processes are at an early stage of development. Figure A34 also illustrates the specific methodological choices considered in each fuel chain which are listed below with reference to the relevant section of the report in which these methodological choices are discussed in detail:

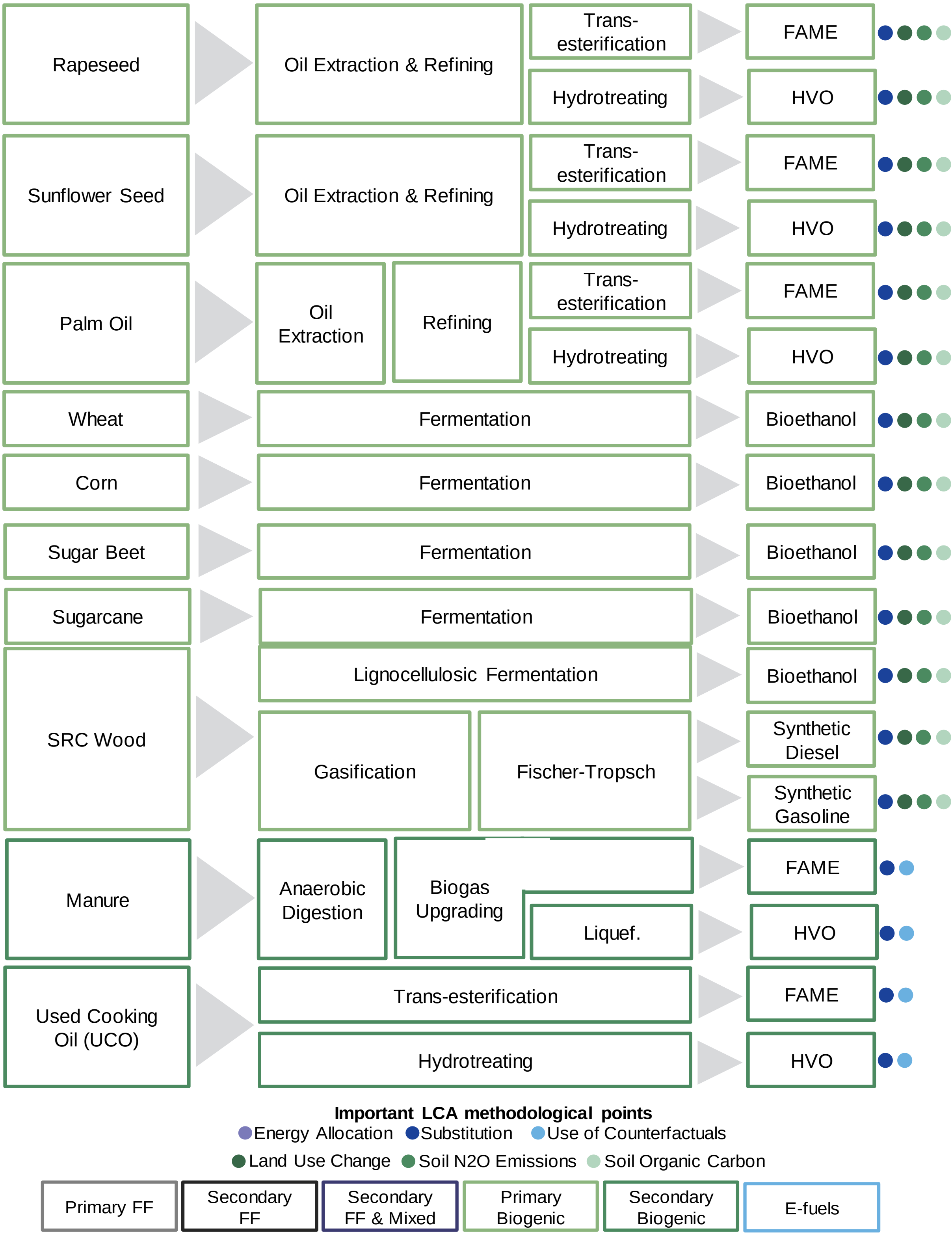
- Energy allocation: 272A3.7.3.1
- Substitution: A3.7.3
- Use of counterfactuals: A3.6.3.3
- Land Use Change: A3.6.3.4.1
- Soil Organic Carbon: A3.6.3.4.4
- Soil N_2O emissions: A3.6.3.4.3

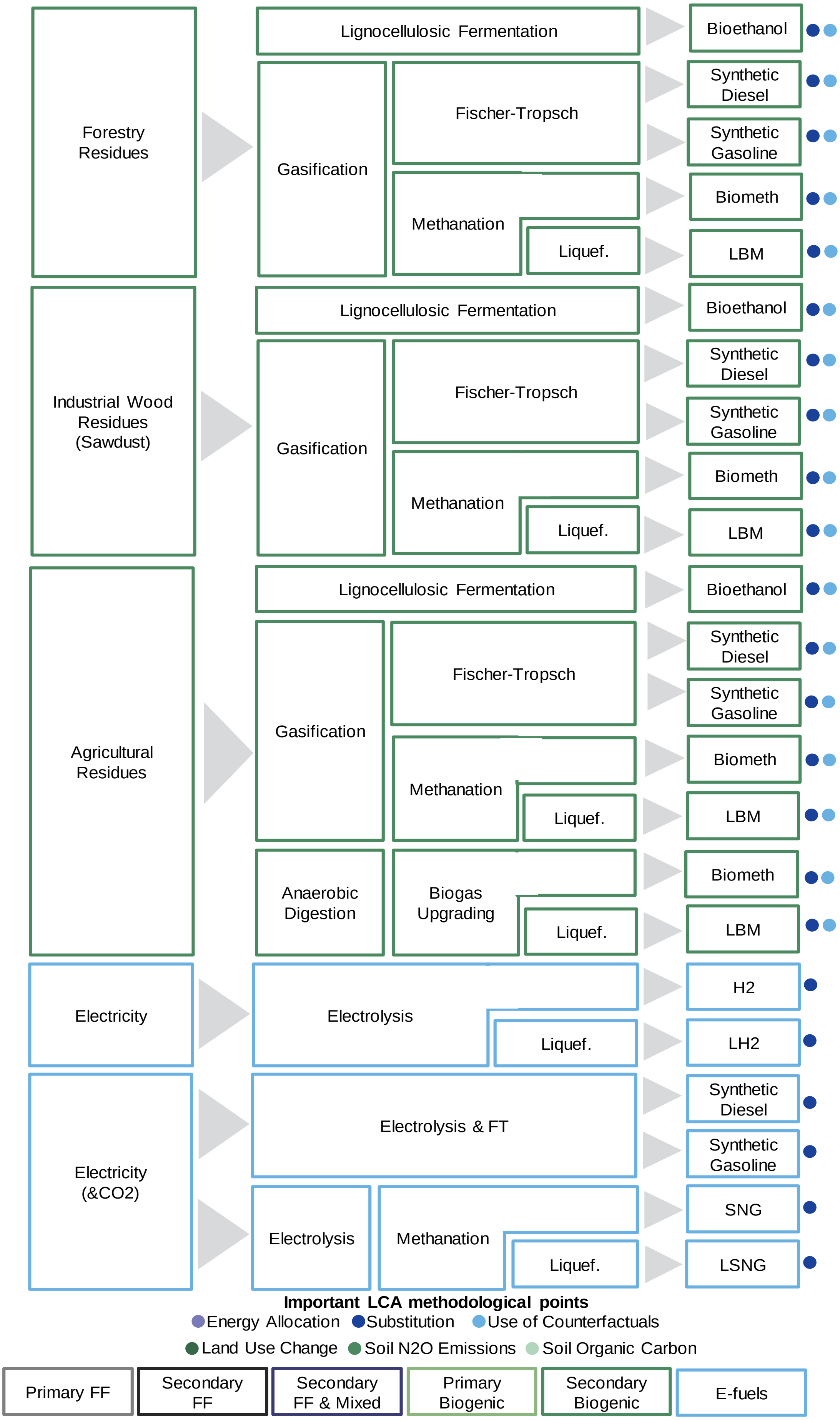
A3.4.3.2 Functions of the product system(s)

All liquid and gaseous fuels under the product system are used for transport.

Figure A34: Illustration of the 59 fuel chains modelled in the fuel chain calculations module




Rapeseed
Oil Extraction & Refining
Trans-esterification
Hydrotreating
FAME
HVO
Sunflower Seed
Oil Extraction & Refining
Trans-esterification
Hydrotreating
FAME
HVO
Palm Oil
Oil Extraction
Refining
Trans-esterification
Hydrotreating
FAME
HVO
Wheat
Fermentation
Bioethanol
Corn
Fermentation
Bioethanol
Sugar Beet
Fermentation
Bioethanol
Sugarcane
Fermentation
Bioethanol
SRC Wood
Lignocellulosic Fermentation
Bioethanol
Gasification
Fischer-Tropsch
Synthetic Diesel
Synthetic Gasoline
Manure
Anaerobic Digestion
Biogas Upgrading
Liquef.
FAME
HVO
Used Cooking Oil (UCO)
Trans-esterification
Hydrotreating
FAME
HVO
Important LCA methodological points
Energy Allocation
Substitution
Use of Counterfactuals
Land Use Change
Soil N2O Emissions
Soil Organic Carbon
Primary FF
Secondary FF
Secondary FF & Mixed
Primary Biogenic
Secondary Biogenic
E-fuels


Forestry Residues
Lignocellulosic Fermentation
Bioethanol
Gasification
Fischer-Tropsch
Synthetic Diesel
Synthetic Gasoline
Methanation
Biometh
Liquef.
LBM
Industrial Wood Residues (Sawdust)
Lignocellulosic Fermentation
Bioethanol
Gasification
Fischer-Tropsch
Synthetic Diesel
Synthetic Gasoline
Methanation
Biometh
Liquef.
LBM
Agricultural Residues
Lignocellulosic Fermentation
Bioethanol
Gasification
Fischer-Tropsch
Synthetic Diesel
Synthetic Gasoline
Methanation
Biometh
Liquef.
LBM
Anaerobic Digestion
Biogas Upgrading
Biometh
Liquef.
LBM
Electricity
Electrolysis
H2
Liquef.
LH2
Electricity (&CO2)
Electrolysis & FT
Synthetic Diesel
Synthetic Gasoline
Electrolysis
Methanation
SNG
Liquef.
LSNG
Important LCA methodological points
Energy Allocation
Substitution
Use of Counterfactuals
Land Use Change
Soil N2O Emissions
Soil Organic Carbon
Primary FF
Secondary FF
Secondary FF & Mixed
Primary Biogenic
Secondary Biogenic
E-fuels

A3.5 Functional unit and reference flows

A3.5.1 Life-cycle functional unit

According to (ISO14040, 2006), "*LCA is a relative approach, which is structured around a functional unit*". The functional unit thus represents the reference product or service to which the input and output flows from the life cycle inventory are related. Due to the comparative character of many LCA's the functional unit plays a critical role and must clearly define the functions (performance characteristics) of the system under investigation. The functional unit also determines the comparability of different studies. Additionally, a quantitative reference flow needs to be defined to which all impacts are normalised.

Important here are also different parameter assumptions which have a significant influence on the utility value of the system under consideration. This applies, for example, to the life-time mileage, driving range, the vehicle segment and engine power. The climatic conditions under which the vehicle is operated can also have a major influence. Such variables therefore need to be considered and defined together with the functional unit, unless they are explicitly to be varied in the analysis.

In life cycle assessments at the vehicle level, both a vehicle kilometre and a vehicle life have been identified in the literature review as the most common reference flows. These reference flows usually lead to a technical comparison of similar vehicles under the same use characteristics as a functional unit. This assumption of the same use characteristics between different technical options often neglects differences observed in real-life, but is used to separate technical differences from usage differences, which may also be due to a political framework (subsidies and taxation). Vehicle life and vehicle kilometres as reference flows can easily be converted using the lifetime mileage - in some publications both values are given.

Mobility-related life cycle assessments based on the utility value of the vehicles (i.e. transport of a certain mass or number of people) are scarcely represented in the literature reviewed. Nevertheless, the variety of vehicle configurations and operating patterns for the analysed commercial vehicles is significantly greater than for passenger cars. This makes it difficult to define a common functional unit for comparative analyses. Only few LCA publications dealing with commercial vehicles have been found in the reviewed literature. In order to do justice to the influence of different payloads, transport performance (tonne-kilometres), for example, is also used here as a functional unit (Lee & Thomas, 2016).

The bandwidth in potential use cases led to the decision to define the functional unit for this study along the lines of vehicle size and utility. The study therefore carries out a technical comparison of vehicles (/powertrain variants) under average European conditions which are similar in size and utility. Size and utility of the vehicle are largely defined by the vehicle type, size class (e.g. GVW) and segment (for passenger cars). This functional unit has also been largely confirmed by the stakeholders.

In the comparison, the same average use characteristics of different vehicle types in terms of life-time mileage and drive profile are considered for all powertrain options (e.g. same assumptions for petrol and diesel vehicles) so that comparisons are provided for equivalent use[44]. This can be varied as a sensitivity analysis. The use characteristics, however, are varied between the vehicle types. For articulated trucks, which are mostly used for long distance haulage, a higher life-time mileage and higher shares of highway driving will be considered compared to private passenger cars.

It is acknowledged that in practice further differences might be associated with different powertrains even for the same vehicle type and segment, such as driving range and maximum speed. These could potentially also affect the life-time mileage and preferred use profile. Nevertheless, such potential differences are neglected in this study. First of all, there is lack of broad evidence for new powertrain concepts which are just entering the market, particularly for heavy duty vehicles. This also leads to a situation where early adopters might have a very different use profile compared to a mass market situation and may thus be only representative for a short time period. It can also be assumed that these powertrains first of all substitute internal combustion engine vehicles (ICEVs) with a similar use profile. In the context of a technical comparison, it is therefore assumed that chosen vehicles are always suited

[44] As opposed to market averages, which factor in a range of other influencing parameters including also fuel prices and other market conditions or user behaviour, which are not the object of study here.

to the specific usage despite differences in driving range and driving characteristics. Vehicles with different powertrain and fuel options are always compared with the same use profile assumed since the focus is on a technical comparison of different vehicle concepts.

A vehicle kilometre is used as the main reference flow in this technical comparison which also has been supported by the largest number of Delphi participants. 29 out 34 respondents regarded this reference flow as essential or highly important. But results will also be given for the vehicle-life as this was also demanded by a number of stakeholders (16/33 regarded this as essential or highly important). For goods vehicles also tonne-km are calculated using appropriate load factors since this reference flow was also demanded by a larger number of Delphi respondents (24/34 regarded this as essential or highly important). This calculation takes into individual vehicle weights and shows the potential influence of different payloads due technical restrictions (e.g. high battery weight). In practice, however, such constraints may not always be applicable since vehicles are not always operated at full load and load restrictions may also be due to limited volume.

A3.5.2 Functional unit for liquid and gaseous fuels

While the functional unit for the complete LCA of vehicles is defined as vehicle kilometre (see above), an intermediary functional unit is used for the evaluation of fuel chains, which is 1 MJ of fuel (final energy) delivered to the tank of the vehicle (Well-to-Tank). Such intermediary functional unit on a per MJ basis is useful to single out impacts from fuels until they reach the vehicle tank and enables integration of the fuel production stage into the full vehicle life cycle. As explained in the following sections, emissions of SO_2 and CO_2 from combustion were added to the “Well-to-Tank” scope of the Fuel Module. For biogenic fuels and e-fuels, the CO_2 emissions from combustion do not contribute to GWP.

Reference flows differ across the different types of liquid and gaseous fuels included in the scope due to the different feedstocks (e.g. crude, natural gas, biomass, electricity, waste, etc) and processing (e.g. hydrotreatment, isomerisation, fractionation, etc.) used to produce fuels.

A3.5.3 Functional unit for electricity

Similar to liquid and gaseous fuels, an intermediary functional unit is also used for electricity. It is defined as 1 MJ (or 1 kWh) of electricity delivered to the grid, in order to allow comparison of different electricity production options. Further downstream different loss ratios do occur with regard on the specific user of electricity: e.g. a large-scale thermal power plant feeds in high voltage electricity to the grid, which needs transport and transformation downstream to the user, whereas electricity from PV in many cases is already low voltage and locally fed into the grid. These diverse loss ratios will be considered according to the actual structure of the respective electricity scenario.

A3.6 System boundaries and cut-off criteria

The **System Boundary** determines which processes are included in the assessment and needs to be in accordance with the goal of the study. Since results from LCA studies can be influenced by selecting favourable system boundaries, they need to be clearly defined at the start of the project and include all relevant processes. In the process of defining the system boundaries, cut-off criteria can be used to reduce complexity of the modelling process.

Cut-off criteria usually specify a minimum contribution to environmental impacts or an amount of material or energy flow to justify an exclusion from the system. By doing this, it is ensured that all relevant contributions to the product system are assessed while limiting the overall complexity of the analysed system to a manageable level. Sometimes also availability of data to perform the study may be taken into account. Nevertheless, any omissions need to be clearly stated and justified within the study.

A3.6.1 Overall life-cycle

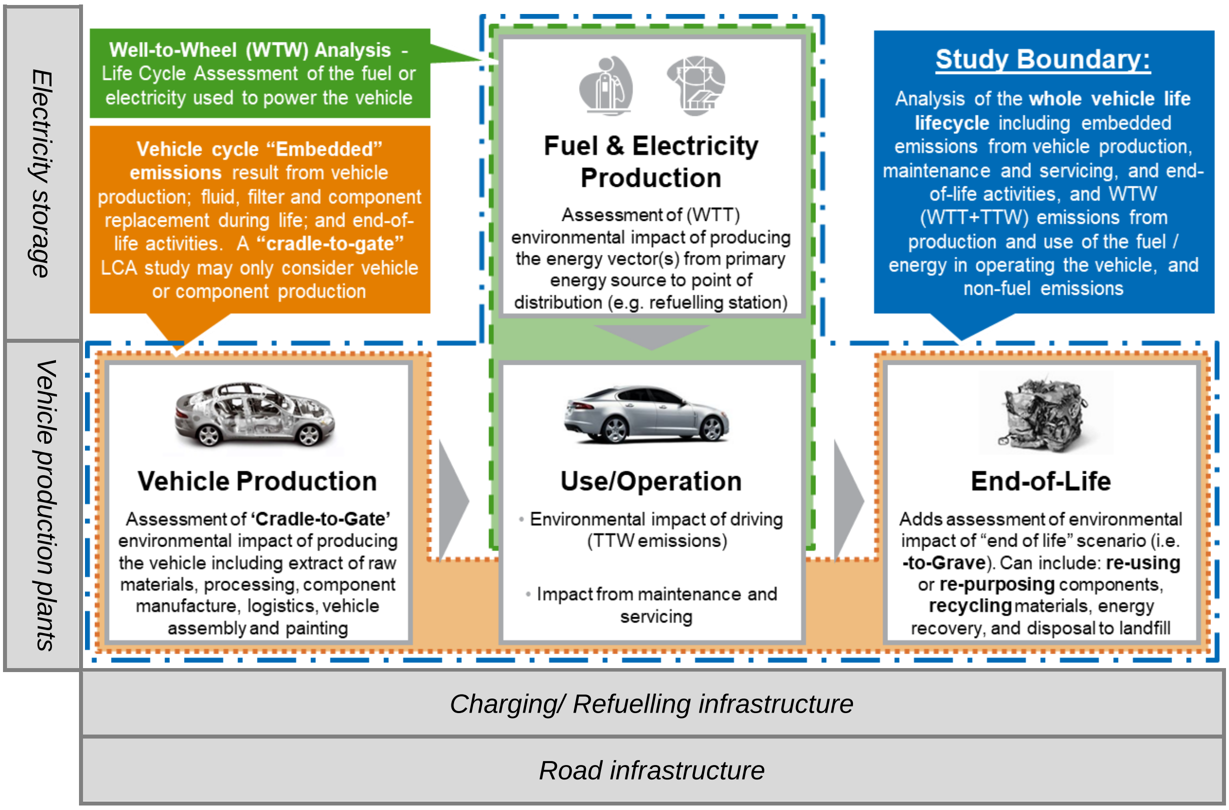
A3.6.1.1 Overall System boundaries

When dealing with lifecycle assessment of light and heavy-duty vehicles different lifecycle stages are involved. The most important lifecycle stage today is the use phase of the vehicles including tailpipe emissions and energy consumption of the vehicles and the respective energy chains (well-to-wheels).

However, due alternative powertrains entering the market a shift in the environmental impacts may be observed and the vehicle construction gains in importance. Here also differences in other areas such as maintenance may apply.

The analysed product system therefore includes all relevant processes directly related to the use of transport vehicles. The methodological boundary thus encompasses the whole life cycle of the vehicles themselves, from manufacturing and fuel and electricity production to the use phase and the end-of-life. An overview of these system boundaries is provided below in Figure A35.

Figure A35: Schematic scope of the assessment (system boundaries)



Notes: The study boundary also includes capital goods for fuel and electricity infrastructure.

In a comparative assessment, capital goods serving the use of transport vehicles only need to be considered if they affect result differences. 22 out of 34 participants in the Delphi survey already (strongly) agreed with system boundaries, mostly not taking into account infrastructure. The following additional considerations have been made in respect for infrastructure:

- Since all vehicles analysed would have comparable impacts for road infrastructure (e.g. streets or parking spaces), these elements have accordingly been omitted from the analyses.
- Charging and refuelling infrastructure could potentially be relevant in a comparative assessment of alternative powertrains (e.g. fast charging, hydrogen pumps, road electrification). Accordingly, infrastructure for charging/refuelling of alternative powertrains had the second highest support by the Delphi participants after electricity/fuels to be included in the assessment: 4 out 9 respondents who answered this question regarded this aspect as essential or highly important. Since charging/refuelling infrastructure was not included in the Commission's technical specification for the scope of this project and as data availability is limited, they are omitted for the time being. Both should be reconsidered for specific technologies (especially electric road systems) if further studies are carried out to update this assessment.
- Impacts from the production of infrastructure are also only partially covered based on their significance and used data:
  - Infrastructure for vehicle manufacturing plants is omitted from explicit characterisation due to the expected low significance (and also consistent with the approaches taken in other similar LCA). Some infrastructure *will* however be implicitly included in the proposed LCI background

database ecoinvent. Thus inventory data for materials used will include materials production infrastructure.

  - In the energy sector infrastructure is relevant when looking at certain renewable energies (e.g. solar power) for which most impacts occur from the infrastructure rather than the generation stage. 6 out 10 respondents who answered this question in the Delphi survey regarded this aspect as essential or highly important. Infrastructure for energy production (electricity and fuels) is therefore fully included; however the detail to which they are characterised varies as described further in chapter A3.6.2 and A3.6.3.

A3.6.1.2 Overall cut-off criteria

Cut-off criteria can be used to exclude processes with a minor impact on overall results and thus reduce complexity of the modelling process. Cut-off criteria usually specify a minimum contribution to environmental impacts or an amount of material or energy flow to justify an exclusion from the system. By doing this, it is ensured that all relevant contributions to the product system are assessed while limiting the overall complexity of the analysed system to a manageable level. Any omissions need to be clearly stated and justified within the study.

Beyond the exclusion of road and charging/refuelling infrastructure as well as infrastructure for vehicle production by definition of the scope, quantitative cut-off criteria are defined for the electricity and fuels cycle which are described in the following sections. For the vehicle cycle no formal criteria are used, since the analysed environmental impacts on a comparative basis are not yet fully assessed within the framework of this study for such an approach. Also specifying minimum material weights will not do justice, since certain environmental impacts may still be significant even for smaller amounts of material. Therefore all known materials and process for vehicle production will be considered in the study. For later updates, cut-off criteria might be introduced based on the results from the application in this study.

Nevertheless, available data on the material used in vehicles/ component not necessarily covers all used materials. If certain materials are not reported in the available data, this introduces an implicit practical cut-off criterion. The reason behind this, however, may differ from other approaches towards cut-off criteria described above. Possible reasons could be non-availability of data in complex product chains, confidentiality in a competitive environment or negligible amounts used.

A3.6.1.3 Time horizon

The time horizon for the study is today (2020) as well as 2030, 2040 and 2050 (two high-level scenarios: Baseline and Tech1.5). The study will focus on establishing today's environmental impacts as a solid starting point for the scenarios. Afterwards technological developments as well as the impacts from various environmental policies will be assessed. The main temporal variations are:

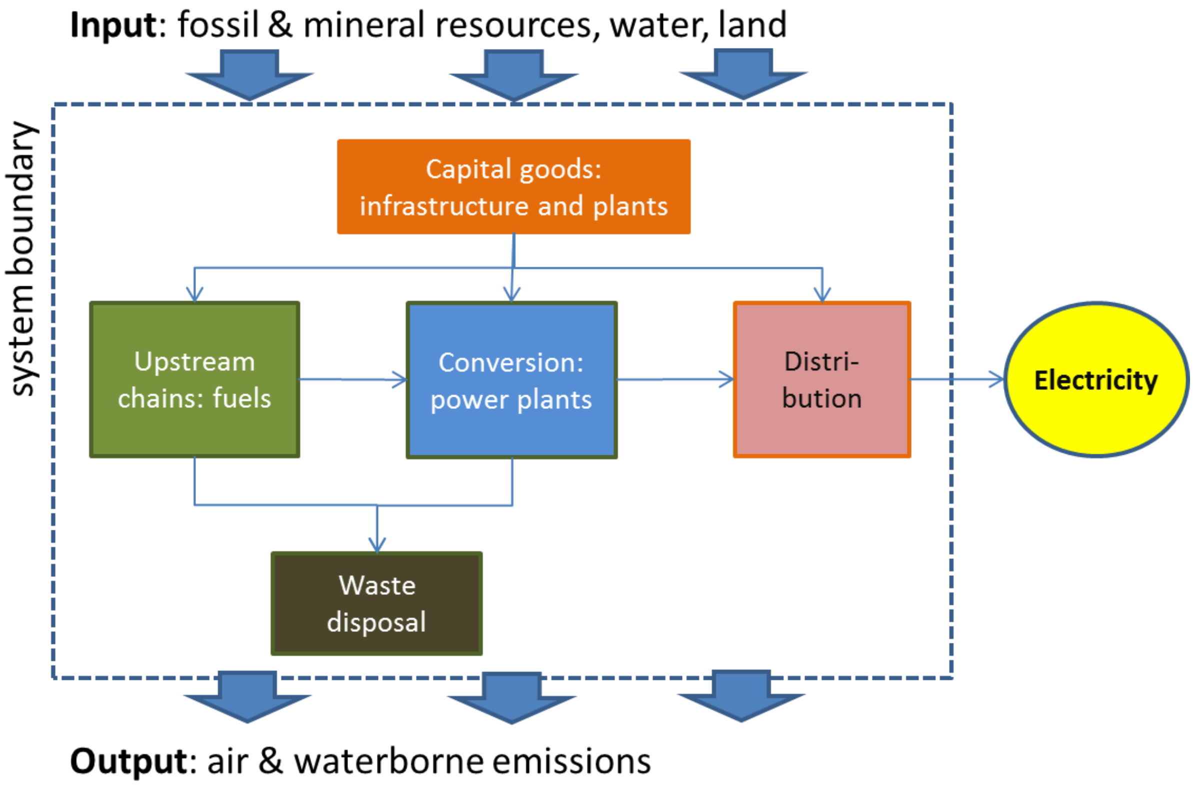
- Changes in the European electricity mixes (due to decarbonisation) which are especially relevant for electric vehicles. Furthermore, power plant efficiencies in the future may be higher than today.
- Changes in vehicle energy demand which are mainly due to an increased efficiency of the conventional or alternative powertrain or results from light-weighting.
- Changes in the fossil and renewable fuel supply which may be due to new fuels or new fuel production processes entering the market or existing fuels having different environmental impacts in the future.
- Changes in vehicle manufacturing which may be due to different materialisation of the vehicles, different vehicle weight or improved production processes and higher recycling rates.
- Changes in the impacts from material production or recycling due to improved processes or decarbonisation of the used energy.

A3.6.2 Electricity production cycle

A3.6.2.1 System boundaries

In order to approximate the impacts of electricity generation as accurately as possible, all relevant life-cycle stages have to be included in the system boundaries. Hence, all directly or indirectly involved relevant processes have to be taken into consideration, starting with the production of raw materials and ending with the disposal of related wastes at the end of the product life cycle ("cradle to grave").

Figure A36: Schematic scope of the system boundaries for the electricity production cycle



Notes: Electricity storage is not included within the system boundary for this project.

A3.6.2.2 Raw material acquisition – Fuels and infrastructure

For the purpose of electricity generation, the acquisition of raw materials can be subdivided into provision of infrastructure-related raw materials on the one hand, e.g. mining of copper for generator coils or sand as an aggregate material in concrete, and raw materials used as fuels on the other, e.g. hard coal or uranium on the other[45]. In addition, further materials in the form of fuels consumed for construction, e.g. diesel fuel in an excavator or for the purpose of material processing are needed, which themselves have to be extracted first.

Infrastructure-related emissions for power generation from **fossil fuels** are negligible compared to end-of-pipe emissions arising during the phase of fuel provision and conversion (Klöpffer & Grahl, 2009).Thus, impacts across the board will be determined by the use-phase and, to a lesser extent, fuel provision. The necessary quantities of materials for each technology are contained in a material bill which aims to accurately replicate the average power plant. However, since LCA always constitutes a simplified picture of reality, material bills usually comprise a finite list of materials and focus on the most important material flows, such as concrete or steel.

In contrast, for **renewable energy sources** (RES) of non-biogenic origin such as photovoltaics (PV) and wind power, infrastructure provision constitutes the most important life cycle stage as their use-phase is virtually emission-free. Hence, raw material acquisition is of vital importance for the results of RES LCA as a whole. Therefore, if the material bill is limited to bulk materials this might pose the risk of oversimplification and subsequently misleading results. For RES of biogenic origin, fuel provision is typically the most significant life cycle stage for impacts. Therefore, raw material acquisition focuses on the supply of fuels, such as cultivation of energy crops, rather than construction of power plant

[45] Fuel provision can also be attributed to the use phase as fuels only need to be supplied during this phase.

components. Similar to fossil fuels, the emphasis regarding the latter is on bulk materials. The system boundaries consist of the extraction of (natural) resources for the mentioned purposes mentioned above, and the release of emissions and wastes accompanying all processing steps (see also Figure A36).

A3.6.2.3 Conversion (power plants)

For **non-biogenic RES**, the impacts during the use phase are of minor relevance, since no fuel has to be supplied nor do emissions arise from combustion or other conversion processes. Moreover, the demand for auxiliary materials is comparatively low.

For **electricity of biogenic origin**, the life cycle inventory is substantially affected by the fuel provision. All processes and materials in the upstream stages of fuel production have to be included in the LCA. For example in the case of energy crops this includes the creation and occupation of acreage, production of fertilisers and plant protection agents, in addition to the combustion-related emissions (such as biogas leakage).

Leakage of biogas is the dominating factor in determining direct emissions for **biogas**, as CO_2 emissions from the combustion of biogas are set to zero[46], following the rationale that the emitted CO_2 has been previously absorbed by the plant. However, since some carbon in the feedstock has been converted to methane (CH_4)[47], biogas leakages are relevant and are particularly significant for GHG impacts given the higher global warming potential of CH_4 compared to CO_2.

In contrast to energy crops, **waste biomass** only carries the burdens from the point of collection and subsequent down-stream processes. This exception is the result of the linking of two product systems: waste disposal services and power generation (see chapter 3.6.3). All processes with accompanying emissions prior to waste collection are attributed to the product system, which produces the waste biomass in the first place.

Fossil-fuel power plants release most of their life-cycle emissions during the use phase, through the combustion of fossil carbon-based energy carriers. Impacts, especially with regard to non-CO_2 emissions, e.g. other pollutants such as SO_2, are mitigated by exhaust gas cleaning and emission control, dependent on the technical framework. The necessary process materials and their respective production and supply have to be factored in, as well, albeit they play an only subordinate role. In addition, emission control requires energy which has a significant influence on the on-site consumption of the power plants.

Although **nuclear power plants** emit little to no direct emissions during plant operation in the use phase, the supply of new nuclear fuel as well as the treatment and disposal of spent fuel rods carries relevant burdens which have to be accounted for.

A3.6.2.4 End-of-Life

Although the decommissioning and subsequent treatment and recycling of power plant components results in emissions and requires energy, their impacts are negligible compared to the other life cycle stages. They are thus a case for the cut-off criteria, as defined below.

A3.6.2.4.1 Cut-off criteria

As described further above, the cut-off criteria is a method to simplify complex product systems by excluding processes or material flows without any noticeable effect on the results. In order to ensure that all relevant impacts are adequately covered, the following cut-off criteria for electricity generation were chosen:

- *Generation technologies*: 1 %: all technologies with a respective share in the European consumption mix (for reference, see Section A3.4.2) of greater than 1 % will be studied.
- *Raw materials / infrastructure*: For conventional power plants: All relevant bulk raw materials (such as steel, concrete, aluminium, etc.) if infrastructure as a whole is greater than 1 % of all impacts. For RES: All materials which account for greater than 1 % on a weight basis.
- *Fuels*: All relevant fuels with a share of more than 5 % with regard to energy content.

[46] Consistently with the overall approach taken for vehicle emissions; e.g. biogenic CO_2 emission from biofuel use (see section A3.6.3); rationale: the impact category GWP characterises biogenic CO_2 as zero.
[47] Typically between 50% and 60% by volume of biogas is methane

- *Environmental Impacts*: Assuming an energy- or mass flow meets the cut-off criteria, but has significant influence on a particular impact category (greater 1 % of the impact category in total), the flow has to be included regardless of the cut-off.

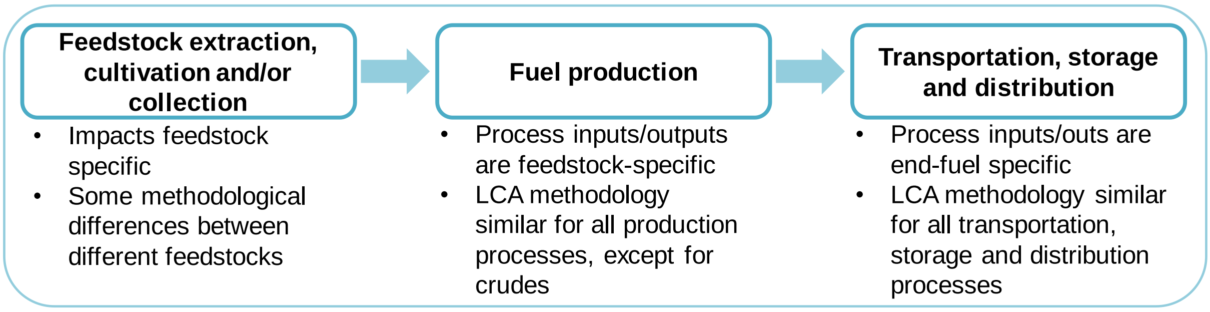
In total, the sum of flows that fall under the cut-off criterion should not exceed 5 % of total mass, energy or environmental impacts. The cut-off criteria apply over the whole timeframe.

A3.6.3 Liquid and gaseous fuel production cycle

A3.6.3.1 General Considerations

The impacts of fuel production are one element in the whole vehicle lifecycle assessment. Taken in isolation, the fuel production LCA system boundary corresponds to what is often referred to as 'well to tank' (WTT) to include all environmental burdens from feedstock production (extraction, cultivation, harvesting, storage, transport, pre-processing) to processing into a fuel (all necessary processing/refining steps) and transport/storage until the fuel reaches vehicle tank (Figure A37). For all fuels, combustion CO_2 and SO_2 emissions were included in the Fuel Module.

Figure A37: Fuel production stages within the general system boundary (Well-to-Tank)



For the purposes of this study five broad categories of fuel chains are considered, depending on the feedstocks used:

- Fuels produced from **primary fossil** feedstocks
- Fuels produced from **secondary fossil** feedstocks
- Fuels produced from **primary biogenic** feedstocks
- Fuels produced from **secondary biogenic** feedstocks
- Fuels for which the energy content comes only from **power (e-fuels)**[48]

The system boundary across all of these fuel types is reflected by Figure A37, but there are key differences in the approach adopted to modelling the environmental impacts of the different feedstocks. These are discussed in more detail in the following sections (A3.6.3.2 to A3.6.3.6).

Further, the impacts associated with capital goods are included within the scope of the fuels' LCA (Module 3). Impacts from infrastructure are included within background datasets by including infrastructure impacts within the background datasets extracted from Ecoinvent. Impacts from foreground infrastructure (e.g. the facility which is used for the production of FAME) have been taken into account by adding an infrastructure flow for all feedstock extraction/cultivation activities and the fuel production facility within the foreground data.

A3.6.3.2 LCA approach for fuels from primary fossil feedstocks

As a result of the stakeholder consultation (Task 3), it was originally intended to evaluate both crude oil extraction and natural gas production (upstream operations) based on the model produced by OPGEE (the Oil Production Greenhouse gas Emissions Estimator). The OPGEE model is primarily used for the

[48] Note that the term Renewable Fuel of Non-Biological Origin (RFNBO) only applies to e-fuels produced entirely from renewable power.

calculation of GHG emissions associated with the production of crude oil and natural gas, and its subsequent processing and transport up to the entrance of the refinery gate. It was originally anticipated that LCI data would be extracted from the model and used to evaluate other LCA impacts (midpoints) during the Life-Cycle Impact Assessment stage.

Practical implementation revealed several challenges to the use of OPGEE data. First, the information available in the OPGEE model did not allow non-GWP impact categories to be comprehensively assessed; second, the model did not include sufficient details to extract foreground data and use them in our life-cycle inventory.

It was therefore decided to:

- Use crude oil extraction data from Ecoinvent (2007) in combination with the ifeu refinery model. The specificities of non-conventional crude refining were modelled by adjusting the refinery parameters (sulphur content and density).
- Model conventional natural gas using the Ecoinvent dataset. A comparison was made with the results obtained by JEC to identify potential discrepancies in the modelling method and data used.
- Use data from GREET for non-conventional natural gas (shale gas), as this is not modelled in Ecoinvent. The use of the GREET database implies specific assumptions, which are more relevant to the US than to the EU. The need to develop additional LCA datasets for non-conventional gas in the EU is further developed in the main report.

Box 7: Additional commentary on proposed approach

The extraction of crude oil and natural gas from oil reservoirs produces a variety of impacts, which are not just limited to GHGs. Given that exploring non-GHG impacts is a key objective of this piece of work, and that the OPGEE model, whilst it has been supported by stakeholders, is limited to producing only GHG impacts, it was a key factor in deciding to switch to use the data sources outlined above.

A3.6.3.3 LCA approach for fuels from secondary fossil feedstocks

Whilst some LCA methodologies to-date do not burden waste feedstocks with any environmental impacts (e.g. RED methodology), this approach may underestimate the environmental impact of diverting waste feedstocks from an existing productive use (E4tech, 2018) (Anthesis & E4tech, 2019). Therefore this study explores the impacts associated with diverting secondary feedstocks from existing productive uses (e.g. MSW combusted to generate heat or power), with the **indirect emissions associated with replacing this useful product assigned to the secondary fossil feedstock**. This 'system expansion' approach brings within the system boundary of fuels produced from secondary fossil feedstocks the environmental impacts of diverting that feedstock from an existing productive use, and consequently replacing the heat or power or other utility that was produced. If through diverting a secondary fossil feedstock to liquid fuel production instead of an existing use, the release of that CO_2 is avoided, then this is treated as a credit (i.e. negative GHG emission) in the GHG intensity of the feedstock. The CO_2 emissions are then counted when the fuel is combusted. This approach aims to avoid either losing or double-counting GHG emissions.

Figure A38: Summary of approach to assessing environmental impact of secondary feedstocks (counterfactual impacts)

Environmental impact of secondary feedstock	=	-	{environmental impact of its previous use}	+	{environmental impact of providing that previous use by another means}

It was only possible in the scope of this study to consider one potential counterfactual use of each feedstock. This aimed to represent a possible counterfactual use of the feedstock, but it was not within scope of this study to do the detailed modelling required to determine whether this would be the most likely counterfactual use of each feedstock. Moreover, the most likely counterfactual use of each feedstock would vary by geography, local economic conditions, and over time. The counterfactual use of all secondary feedstocks apart from manure was assumed to be combustion with electricity generation. Manure is assumed to be diverted from use as a fertiliser on the fields.

There are also a range of possible products that could replace the secondary feedstock when it is diverted to transport fuel production. In particular the average way of providing that utility may be different to the marginal way of providing one additional unit of that utility when the feedstock is diverted to transport fuel production. In this study, the average way of providing that previous use of the feedstock by another means was modelled. For those feedstocks for which the counterfactual use is combustion with electricity generation (i.e. all secondary feedstocks apart from manure) European grid average electricity is assumed to replace the electricity previously generated by that secondary feedstock.

It was originally envisaged that waste CO_2 used in the production of fuels (e-fuels) would be treated in the same way as secondary fossil feedstocks. Under this approach, if the CO_2 had previously been emitted to the atmosphere, the fuel chain is credited with avoiding the release of that CO_2, and then the burden of CO_2 released during fuel combustion is also assigned to the fuel chain. For reasons of practicality and transparency this approach was not in the end adopted in the tool. Instead, it is simply assumed that any CO_2 used in the production of e-fuels would have been emitted to the atmosphere, and therefore the CO_2 emissions from the combustion of the e-fuel in the engine do not contribute to GWP.

A3.6.3.4 LCA approach for fuels from primary biogenic feedstocks

Primary biogenic feedstocks are produced in agricultural or forestry operations, which due to their close interaction between the technosphere (human / industrial processes) and the biosphere, have some specific LCA methodological issues, which must be addressed, including:

- Land use change
- Inputs to crop cultivation
- Direct field emissions

A3.6.3.4.1 Land-use change

Land-use change (LUC) is caused by the conversion of land from an initial state (e.g. forest, savannah, crop field, plantation, etc.) to another state. It is accompanied by GHG emissions due to the release of carbon contained in the soil and biomass (both above and below ground). LUC is directly observed in the area used to cultivate feedstocks which are converted to biofuels.

LUC may also occur in other locations whenever biofuel production diverts biomass (including food and fodder crops) from other uses (e.g. food, feed, fibre, construction, etc). As a reaction to their available supply decreasing, other sectors using biomass may trigger more land conversion to produce additional biomass. This market-mediated land-use change (also known as iLUC) must be assessed using global socio-economic models to model the complex interactions between supply, demand and pricing in different sectors of the economy. These models are highly dependent on the input data and assumptions that go into making them and provide a wide range of results for the indirect land use change associated with the cultivation of various biofuel feedstocks. Generally, the models do not differentiate between direct and indirect land-use-change, they simply assess the consequences of crop demand changes on land area (Marelli, et al., 2015).

in line with the literature review and stakeholder consultation, land-use change estimates and resulting GHG emissions were obtained from the GLOBIOM model and added to the corresponding midpoint used at the LCIA stage (GWP). Since the GLOBIOM values also include Soil Organic Carbon emissions, these were not considered separately.

GLOBIOM values are disaggregated for each crop (e.g. wheat, sugarcane, palm, etc), unlike RED II, which uses average values per crop category (sugar/starch crop, oilseed), which provides a more accurate estimate. The GWP amortization period in GLOBIOM is set at 20 years, which is shorter than what other studies suggest. No alternative time (e.g. GWP100) was tested during this study, which could constitute a relevant sensitivity to test in future research.

Box 8: Additional commentary on proposed approach

The suggested approach did not obtain a large majority among participants to the stakeholder consultation. While some stakeholders were keen for this methodology to be consistent with the current EU regulatory framework (iLUC is not included in the GHG emissions of biofuels in the Renewable Energy Directive), others considered that the inclusion of iLUC is paramount to the accurate evaluation of the GHG intensity of biofuels. Some stakeholders also disagreed with the use of economic models to characterise iLUC. Finally, the mere distinction between direct and indirect LUC was also challenged by a few stakeholders, hence the attempt to avoid using these terms since the proposed model (GLOBIOM) would address both at once.

A3.6.3.4.2 Inputs to crop cultivation

Generally, inputs required for crop cultivation are included in the system boundary of a fuel LCA. These can usually be considered in the same way as any other inputs to an industrial process, but there are some elements specific to cultivation system inputs that require particular consideration: multiple cropping systems, perennial crops, and variability in emissions from agricultural inputs.

Fuel use for farm machinery is generally included within the system boundary of a biofuel LCA. Fuel use is impacted by both tractor power and soil type (Williams, Audsley, & Sandars, 2006). The specificity of the LCA study and availability of data shall inform the level of granularity of the assessment.

Inputs to crop cultivation were modelled by using Ecoinvent datasets, as follows:

Crop	Dataset used in Ecoinvent
Corn	Maize grain, Swiss integrated production {CH}| production | APOS, U
Palm	Palm fruit bunch {ID}| palm fruit bunch production | APOS, U
Rape	Rape seed {FR}| production | APOS, U
Straw	Straw {CH}| wheat production, Swiss integrated production, intensive | APOS, U
Sugar beet	Sugar beet {FR}| sugar beet production | APOS, U
Sugarcane	Sugarcane {BR}| production | APOS, U
Sunflower	Sunflower seed {FR}| sunflower production | APOS, U
Wheat	Wheat grain {FR}| wheat production | APOS, U
SRC	Wood chips and particles, willow {DE}| willow production, short rotation coppice | APOS, U

Datasets were customised to remove LUC emissions (these are added separately, along with SOC, via GLOBIOM values -see previous section) and change N_2O emissions to those calculated using the JRC Global Nitrous Oxide Calculator (GNOC) (see section A3.6.3.4.3).

A3.6.3.4.3 Direct field emissions

Agricultural activities such as tillage, fertiliser use, and harvesting can cause N_2O to be emitted directly to the atmosphere from soils. N_2O emissions depend on agricultural practices and environmental factors such as soil type, land topography and weather conditions (Edwards, et al., 2017).

Indirect N_2O emissions result from transport of nitrogen from agricultural sites into water, or emissions as ammonia or nitrogen oxides which cause N_2O production elsewhere.

N_2O emissions were modelled through the GNOC values, as detailed in JEC's WTT calculation sheets (V5), based on JRC internal calculations. These values were used to customise the Ecoinvent datasets (section A3.6.3.4.2) used for crop cultivation.

A3.6.3.4.4 Soil organic carbon

Losses in soil organic carbon (SOC) can be significant in certain situations, for example when implementing intensive agriculture. In this study, SOC values were included under the LUC emissions from GLOBIOM (See above), thus adding to the GWP score at cultivation stage.

A3.6.3.5 LCA approach for fuels from secondary biogenic feedstocks

Secondary biogenic feedstocks are residues from other agricultural or industrial systems (e.g. wood processing, crop harvesting). In this study they are defined following the definition of EU RED II, i.e. a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it. By using this definition, rather than one which is dependent on the relative price of the secondary material compared to the primary product alongside which it is produced, the definition of certain feedstocks as ‘secondary’ does not fluctuate according to demand or price.

The environmental impacts associated with secondary biogenic feedstocks were assessed in the same way as for secondary fossil feedstocks. This is a system expansion approach so that in cases where the secondary biogenic feedstock was diverted from an existing productive use (e.g. straw combusted to generate heat or power), the indirect emissions associated with replacing this useful product were assigned to the secondary biogenic feedstock. More details on this approach are given in section A3.6.3.3.

A3.6.3.6 LCA approach for E-fuels

E-fuels are fuels for which the energy content of the fuel comes directly from an energy source. For all of the e-fuel chains considered in this study the energy source for the fuel was electricity. The system boundary for e-fuels includes the electricity required to produce the e-fuel, which was treated in the LCA tool in the same way as process electricity used for the production of all other fuel types. Because the majority of the environmental impacts of the e-fuel are due to the source of the electricity, the ability to vary the source of the electricity was built into the tool as a sensitivity. It was originally envisaged that waste CO_2 used in the production of fuels (e-fuels) would be treated in the same way as secondary fossil feedstocks. Under this approach, if the CO_2 had previously been emitted to the atmosphere, the fuel chain is credited with avoiding the release of that CO_2, and then the burden of CO_2 released during fuel combustion is also assigned to the fuel chain. As long as the CO_2 used in the production of e-fuels is a waste that would have been released to the atmosphere, this approach would have resulted in a ‘credit’ of CO_2 for the fuel chain exactly balanced out by a release of CO_2 during fuel production and combustion.

To simplify the construction of the tool, this ‘credit’ and ‘release’ of CO_2 is not explicitly shown. Instead it is assumed that the CO_2 used in the production of e-fuels is a waste which would have been released to the atmosphere, therefore there is no net release or sequestration of CO_2 when it is used to produce an e-fuel which is combusted in a vehicle. In the tool there is therefore no differentiation between the use of fossil or biogenic CO_2 in the production of e-fuels: as long as the CO_2 is a waste that would have been emitted to the atmosphere anyway, the net impact of using it for e-fuel production is the same regardless of whether it originally came from biogenic or fossil sources.

The impacts from capture and purification of CO_2 from an industrial point-source are included within the system boundary. CO_2 capture using monoethanolamines is assumed. The inputs, including monoethanolamines, electricity and heat required for this process are taken into account in this study.

A3.7 Multi-functionality

A3.7.1 Overview

A3.7.1.1 LCA approaches

Two different general LCA approaches are distinguished and used in the available literature:

- **Attributional approach** means that the inputs and outputs of a system are attributed to the functional unit by partitioning the unit process according to a normative rule. Generally, attributional LCA is well suited for products that are already offered on the market and where changes in production do not result in any large-scale consequences. It can therefore be used to establish a baseline for the product system and to assess today's impacts from road transportation.

- When decisions are being analysed that may result in large scale changes of the road transport system, a **consequential approach** might be needed. This might be the case for specific parts of the product system in the scenarios (mostly fuels and electricity for future applications in road transport). In a consequential LCA, activities are linked to include all aspects that are supposed to be changed as a consequence of a change in demand for the specific product into a system. Since the scenarios will include variations of system assumptions, possible consequences of these assumptions will be considered by the scenarios.

With the reviewed literature, no study on the whole vehicle life cycle today following a fully consequential approach was identified. Against the backdrop of the broad scope of the study, a consistent attributional approach was identified as appropriate from a feasibility point of view, since "balancing available resources for application" was also defined as a criterion for methodology development. But since the scope of the study also comprises scenarios for future impacts until 2050, consequential aspects cannot be fully neglected. Therefore, a partially mixed LCA approach was proposed for use in the study. The Delphi survey largely signalled support for this partially mix approach: 24 out 34 respondents agreed or strongly agreed to this approach. Those that (strongly) disagreed with this mixed approach also had mixed views on the best approach. As areas for which a consequential viewpoint was regarded as essential or highly important, electricity (18/23), alternative fuels (14/23) and battery production (17/23) have been identified by the Delphi participants.

It was therefore decided to mostly use an overall consistent attributional approach as a solid baseline impact assessment, which also follows the recommendation in the ILCD handbook. For fuel chains, however, elements of consequential LCA are used as a sensitivity to evaluate the impact of diverting secondary feedstocks from its counterfactual use to fuel production. Such diversion may avoid certain environmental impacts (e.g. avoided incineration of waste), but also induce additional impacts (e.g. if some waste or residues are diverted from electricity production, additional grid electricity may be needed in compensation), which can only be appraised via consequential LCA.

Further consequential impacts could potentially occur in the material chains. These, however, are not usually considered in the respective background data. Here only certain consequential elements (new battery cell chemistries, higher process efficiencies through economies of scale, electricity split and decarbonisation of materials) are considered in the scenarios for modelling of battery and fuel cell production. This does justice to the stakeholder request in this area.

This approach of using consequential elements only for selected stages is also in line with the analysed LCA literature, where almost no studies apply the consequential approach to the whole vehicle life cycle. This is expected to be also due to the higher complexity of a consequential approach also applying to this study.

A detailed description of the consequential LCA approaches used in the electricity and fuels cycle is given in sections A3.7.2 and A3.7.3.

A3.7.1.2 Multi-functionality

The modelling approach is also related to multi-functionality, i.e. when a process results in more than one product. For this a three-step procedure/hierarchy is defined in (ISO14040, 2006) which is largely followed in the project:

- **Subdivision** of the product system is described as the preferred option. Here a multifunctional black box unit process is subdivided into mono-functional single operation unit processes thereby cutting free the required process and avoiding the need for allocation/ substitution.
- When this is not possible, a **system expansion** (expanding the system to include the function of the co-product) or substitution (credit for the supplied co-product) is done.
- Thirdly, an **allocation** according to preferably physical or other parameters of the co-products is possible. When doing an allocation, different physical properties of a product may be used (e.g. an exergetic allocation is common for energy resources). When no physical relationships can be observed, an economic allocation may also be feasible.

Multi-functional processes mainly occur for the electricity and fuel chains and treatment with them is described in more detail in the next sections. In vehicle production multi functionality is either covered already in the energy chains or concerns material chains and is thus be implicitly considered in the background data base.

A3.7.2 Electricity

A3.7.2.1 LCA approach

As a default, life-cycle analysis of electricity generation will follow an attributional approach (see Section A3.6.3) for the status quo as well as future scenarios.

In order to provide an overview of the range of possible results with respect to electricity mix composition, two alternative scenarios were utilised in the electricity and wider modelling (a baseline scenario and a high decarbonisation scenario, based on EC modelling for the long-term strategy).

Further information is also provided in the next subsections on how multifunctionality and consequential issues are handled in the methodology, i.e. for CHP (combined heat and power) and for waste incineration. These are only two elements relevant to the electricity chain analysis that have, and account for only a very small share of the overall EU electricity generation mix.

A3.7.2.2 Combined heat and power generation

The production of electricity, particularly in the case of fossil-fuelled combustion plants, can additionally produce heat of varying temperatures, dependent on the technology. The intended application of the heat is primarily a function of its' temperature[49]. The ratio between (district) heat and power output is to a degree adjustable and dependent on the power plant type. In contrast to a product system with a single output, power generation as described constitutes a multi-output system. An assignment of the respective burdens on electricity and district heat is therefore necessary and realized through allocation based on the concept of exergy. Exergy describes the part of the energy of a system that can carry out mechanical work. The assignment of an exergy value to the generated electricity is performed by applying a factor of C_{el} = 1, implying that all energy from electricity can be made available for mechanical work. The exergy content of heat is evaluated using the Carnot efficiency, which is calculated via the following formula:

$C_h = \frac{T_h - T_0}{T_h}$ with T_h = temperature of available heat in Kelvin and

T_0 = environmental temperature, set to 273 Kelvin (0°C)

If for example C_h equals 0.5 to C_{el} = 1, then 2/3s of the burdens (EF_{heat}) will be allocated to electricity, following:

$$EF_{heat} = \frac{C_h}{(C_h + C_{el})} * Emissions_{total}$$

A3.7.2.3 Waste incineration

The emissions from, and resource requirements for, waste incineration are allocated to the waste disposal service. As a consequence the supply of energy from waste incineration only carries minor burdens (comparted to fossil fuel generation), since in this case, a linking between two different product systems occurs.

A3.7.3 Liquid and gaseous fuel production cycle

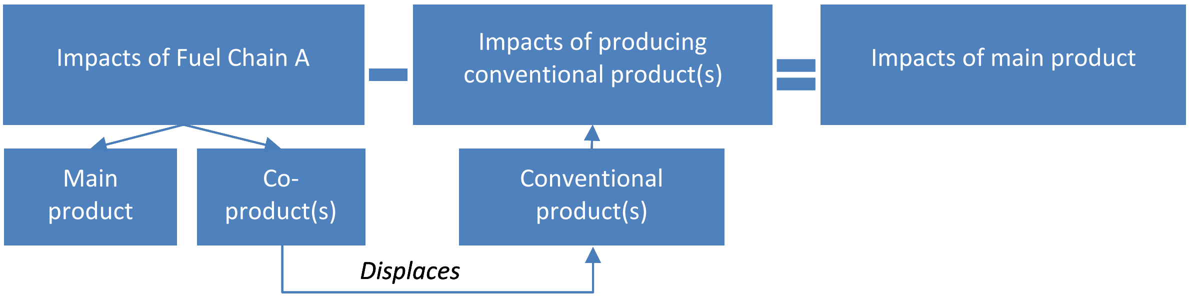
The ISO standard provides a decision hierarchy to address multifunctionality within a process. The preferred method is to subdivide a given process into separate sub-processes to avoid the production of co-products. However, for many of the fuel chains examined in this study, the available foreground data does not subdivide the process. The next method to address multifunctionality, according to the hierarchy, is to expand the product system to include the additional functionality related to the co-products – termed substitution method onwards. The substitution method was used to account for the production of co-products in the fuel production cycle, with a notable exception of crude oil refining. As part of the ifeu refinery model, multifunctionality in crude oil refining is addressed by using an energy

[49] Other factors, such as settlement density or transport distances, the availability of customers etc. also factor in, albeit to a lesser extent.

allocation, whereby impacts are divided among co-products relative to their energy content (see below for greater information).

In the substitution method, the existing product in the market which could be replaced by the co-product from the fuel production system are identified, and the impacts of producing these existing products are quantified. These impacts are then subtracted from the impacts generated in the system being investigated, to reflect that the impacts of producing that existing product are avoided due to the production of the co-product. Figure A 39 illustrates the substitution method. The impacts associated with producing conventional products are based on Ecoinvent modelling for all co-products, except co-products which would displace conventional diesel, gasoline, natural gas or electricity. In the cases where the co-product can substitute out diesel, gasoline and natural gas, the displacement credit is equivalent to their impact (up to point of production) as already modelled in the fuels' module under their respective chains. Where electricity is produced as a co-product, the substitution credit is equivalent to electricity impact as modelled in Module 2.

Figure A 39: Illustrative diagram of the substitution method



Using the substitution method to account for multifunctionality differs from the method employed by the Renewable Energy Directive (RED) to calculate the GHG impact of biofuels. Based on the methodology described in the RED Annex V, impacts should be divided between the main product and its co-products in proportion to their energy content, a method known as energy allocation. Allocation is applied to all impacts generated up to and including the process step in which the co-product is produced.

A3.7.3.1 Multifunctionality in crude oil refining

Petroleum refineries produce a wide variety of products for use in the fuels and chemicals sector. This means that it is necessary to carefully consider the burden that each of these products ought to carry. Following the preference in ISO 14040 for subdivision of processes, the approach taken in this project is to follow the various processing steps within the refinery boundary assessing each according to the physical relationships of inputs and outputs. This approach was elaborated by Fehrenbach et al (2019) (hereafter referred to as the 'ifeu model') and summarized below.

ifeu Model Overview:

Unlike some other refinery models which tend to consider a refinery as a black-box, the ifeu refinery model calculates in a step by step way, the complex network of refinery processes (atmospheric distillation, vacuum distillation, visbreaker, hydrocracker, etc.), and gives an integrated sum of all connected modules. The allocation is executed within each of these steps, allowing the implementation of the allocation rules at process step level separately and globally, over the system of all steps. The environmental "backpack" of each final product is allocated automatically by the LCI functionality given in UBMERTO.

ifeu model allocation procedure:

The allocation approach implemented within the ifeu refinery model is designed to consider:

a. the complexity of the production system;

b. the valuation of the products (upgrading/downgrading of feedstock material during a specific process);

c. real physical mass flows.

In the model, impacts are allocated to different refinery products according to the following four rules:

1. In general, allocation is weighted according to the products' energy content, i.e. their lower heating values

2. The burdens for the first step of separation (atmospheric distillation) are allocated to all co-products, including the atmospheric residue (bottom product)

3. The burdens for any subsequent process step that is intended to reduce the quantity of non-intended products (i.e. vacuum distillation and cracking) are allocated to all co-products except for exactly the non-intended bottom products (e.g. vacuum residue, cracking residue; see definition below of the term "residue" – note that LPG may also be considered as a non-intended product, therefore "non-intended" is also defined within that box).

4. Retention of feedstock: The 3rd rule refers to the allocation of the respective process burdens; it does not include the allocation of feedstocks. The input material (feedstock) into a refinery process step is always allocated according to the 1st rule: e.g. visbreaker residue takes 40 % of the totalized co-product output of a visbreaker cracker, thus 40 % of the visbreaker input (vacuum distillate) and its upstream burden is allocated to the visbreaker residue

Summary of implications of using this method:

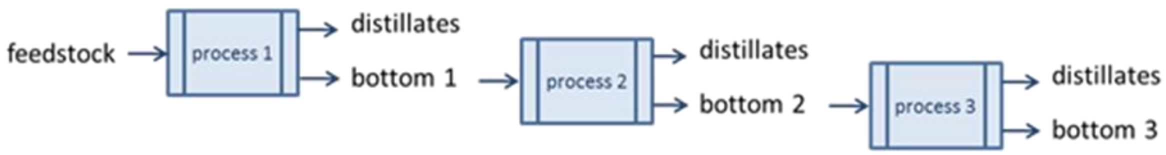
Impacts associated with the refinery are allocated to its various products as follows:

- The LCI of every refinery product includes the burden of producing at least 1 MJ crude oil per MJ product feedstock; considering that some refinery products have lower heating values than crude oil (e.g. petroleum coke or heavy fuel oil), such refinery products enclose less than 1 kg crude oil per kg product;
- Final products derived from sequential processing accumulate higher "backpacks" than products derived predominantly from straight-run. An exception is the heavy products derived from bottoms. Even if they pass a cascade of cracking processes, without rules 3 and 4, heavy fuel oil would be the product with the highest backpack, which would contradict any value-based perception of the refining business.

Additional definitions:

<u>Residues:</u> residues are always treated as co-products, never as waste – despite having certain "waste attributes". The combined allocation procedure adopts ISO's consideration of "partly co-products and partly waste" according to the following scheme:

Figure A40: Illustration of definition of co-products and residues in Ifeu model



- Bottom 1 is one of the co-products from process 1 and therefore treated like all co-products (distillates and bottom) from process 1.
- Bottoms 2 and 3 are non-intended outputs from processes 2 and 3, respectively, because these processes are intended to reduce the occurrence of residuals. Consequently, they don't carry any burdens from process 2 and process 3, respectively. The "co-product part" is connected with the attribution of feedstock and expenditures/emissions from process 1, while the "waste part" is reflected by neglecting expenditures/emissions from process 2 and 3.

<u>Non-intentional co-products</u>: Given the complexity of the configuration of refineries and the multitude of co-products, defining the primary aims of running a refinery is challenging. Consequently, the model under discussion adopts the following step-wise approach to distinguish between intended and non-intended co-products:

i. Step 1: final products with market prices higher than crude oil are considered to be intended.
ii. Step 2: final products with market prices lower than crude oil but which supply basic products for markets which cannot be served easily by alternative products (e.g. bitumen) are considered to be intended.
iii. Step 3: intermediate outputs, which are not traded as standard refinery products (e.g. vacuum residue) are always straightforward according to the allocation rules as defined: bottom products (output) made from bottom products (input) are always non-intended.

As a result, only heavy fuel oil (HFO), refinery Sulphur, vacuum residue and cracker residues are considered non-intentional.

Box 9: Additional commentary on proposed approach

The refinery analysis used by CONCAWE was supported by several stakeholders during the consultation process. It differs from the allocation approach of ifeu, but is the method used by the oil industry since the 1950s to calculate the crude oil needed to produce different products.

Previously, as described in JEC 2018 (JEC - Joint Research Centre; EUCAR; CONCAWE, 2014a), Concawe proposed an 'incremental' methodology focused on gasoline and diesel fuel and based on marginal analysis using its in-house EU refining model. Starting with a counterfactual case, a small change of demand for either fuel was introduced and the resulting change in CO_2 emissions was apportioned to that change in demand. Whilst it delivered figures that were considered realistic there were significant drawbacks. Firstly the approach only worked well with major products and secondly the CO_2 intensity figures were not additive (i.e. the sum of all marginal intensities would not exactly equal the total emissions of the refineries represented by the model), thereby not meeting one of the requirements of Life Cycle Assessment (LCA) studies.

Therefore, Concawe has recently changed to a 'simultaneous constraints' method, as described in Concawe (2017). This method seeks to represent the combined and simultaneous impact of all system constraints, including both product sales and maximum unit capacities, and addresses the additivity criterion. It is worth noting that it yields marginal CO_2-intensity values that can be expected to be lower than the previous 'incremental' method.

The following considerations were taken into account when making the decision to use the ifeu method, rather than the CONCAWE method:

- The approach described by CONCAWE is used by refiners to make decisions around economic optimization of the refinery – e.g. how the change in production of one product would increase the crude oil demand of the whole refinery and the resultant impact on refinery emissions. However, this approach can lead to some products, such as heavy fuel oil or petroleum coke, having negative refining emissions, (even if their overall carbon footprint, which includes combustion emissions, is still positive). Some stakeholders have trouble understanding this. Furthermore, this is a long term study, wherein fundamental large scale shifts in the transport fuel mix are envisaged. To take this into account using CONCAWE's method, the refinery model and operating parameters would need to be updated to reflect the future mix of product demand. The consortium does not have a way to do this.
- A key objective of this study is to go beyond what has already been carried out in other well-to-wheel LCA studies and to look at non-GHG impacts. Given that the CONCAWE model does not have the ability to model non-GHG impacts, this was another important factor in deciding to use the ifeu model, which does have this capability. It can model impacts including air pollution, water emissions and catalyst production and waste.

In order to understand the implications of using the chosen methodology (Ifeu model) rather than the CONCAWE model, the refinery GHG allocation results from this study were compared against those from JEC 2018 (which was based on the CONCAWE model described in Concawe (2017)), to understand the key differences. Note that this was only possible for GHG emissions, as the CONCAWE model does not model the non-GHG impacts.

A3.8 End-of-life modelling for vehicles

A3.8.1 EoL approach for vehicles

End-of-life (EoL) modelling has been broadly discussed methodologically within the LCA community in recent years, but there is no consensus on the single best approach. This was also reflected in the Delphi survey in which no single approach had a clear majority.

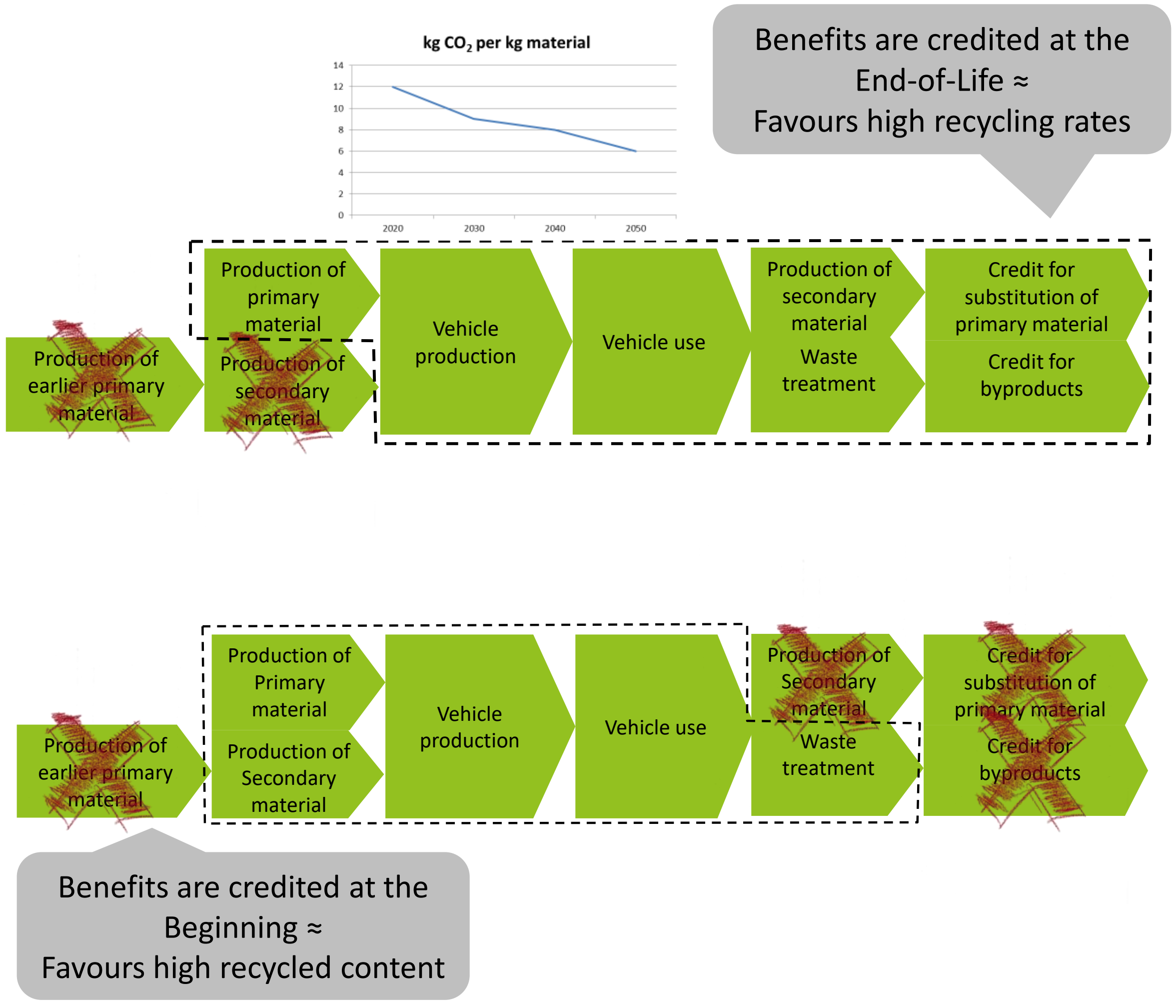
One possibility to handle recycling is to have a **closed-loop** recycling. This ideal case is often not usable in reality, since a downgrading of the recycled materials and a time lag between primary and secondary use occurs. Therefore, other approaches are often applied of which the following have been identified as common options in the literature review:

- **Avoided-burden approach (0:100)** (also referred to as "End-of-Life" approach): The secondary material may (partially) substitute a primary material, which results in a credit for the recycling process. This approach is taken in Gabi, where a value-corrected substitution is done.
- **Cut-off approach (100:0)** (also referred to as "recycled content" approach): A cut-off between the primary and secondary system is performed. Here, the primary user receives the full burdens for the waste treatment, but no burdens for recycling. No credit for recycling or waste treatment of by-products is given and a simple cut-off is performed. This encourages the use of secondary material as an input, but not the waste treatment with beneficial by-products. This method is used in the ecoinvent 3 database for the system model "recycled-content cut-off".
- If the primary and secondary user of a certain material is known, a **50:50** approach may also be taken**.** Here all environmental impacts are shared between the two products systems, so that each gets 50 % of those. This approach is, however, only feasible when both product systems are known and therefore has a lower relevance in LCA practice today.
- Another possibility is to perform an allocation between the primary and secondary usages of a material. This method is closely linked to the ecoinvent database and is used in its system model "**allocation at the point of substitution**" (APOS). Whenever a marketable product results from a waste treatment process, an economic allocation is done. This system model encourages the waste producers to recycle and reuse their products as far as economically feasible.

The two most common approaches today are the cut-off and the avoided burden approach. The sole use of both approaches, however, did not receive large support by the Delphi respondents due to certain deficits. For the vehicle materials life-cycle (as illustrated in Figure A41) it has to be taken into account that there is a time lag (i.e. the vehicle life) between production (with a defined recycled content) and the actual recycling (i.e. future recycling rate). Within this vehicle-life, recycling rate and carbon intensity of materials production (defining the appropriate credit) may be subject to changes. This means:

- The avoided burden approach rather favours a high recycling rate which is common for many vehicle materials, but bears risks since a credit is given today for a potential benefit from recycling in the future. Here uncertainties arise in respect to the actual recycling rate and also the appropriate quantitative credit at the vehicles end-of-life.
- The cut-off approach in turn encourages the use of secondary material as an input, but not the waste treatment with beneficial by-products. This approach is more stable from a policy maker viewpoint, since recycled content is usually well known, while future recycling rates and credits have to be estimated based on the current situation. On the other hand, the role of the automotive industry as a potential supplier of materials for recycling is not reflected. While up to 90% of metals may be recycled at the end-of-life, the amount of secondary material in the market is much lower. In addition, for materials like carbon fibre, that are not currently recyclable, new recycling processes are being investigated that could be applied in the longer-term timeframe considered in this study (i.e. to 2050).

Figure A41: Schematic presentation of avoided burden (upper figure) and cut-off approach (lower figure)



To account for the different situations in respect to recycled content and recycling rate, a **hybrid approach** was initially proposed to account for the very different situations in respect to recycled content and recycling rate. This approach is consistent with the PEF (Product Environmental Footprint) 'Circular Footprint Formula' (PEF CFF) also included in the battery PEFCR (Product Environmental Footprint Category Rules) (RECHARGE, 2018), though it is a more simplified form. In the PEF CFF an allocation factor between the first and the second user of a certain material is introduced, as well as factors to account for a potential difference in quality of virgin and recycled materials. This formula basically covers the cut-off and avoided burden approach as marginal cases, and was the choice favoured by majority stakeholders during the consultation for this project, though there was no consensus.

Approaches to End-of-life (EoL) modelling have been broadly discussed within the LCA community in recent years and while there is still no overall consensus on the single best approach, there is a growing trend towards using the PEF CFF (JRC, 2018a)[50] methodological approach in the EU. From a legislative context, the question surrounding treatment of EoL is whether the focus is more on promoting recycling, or use of secondary materials. The PEF CFF has been developed, in part, to account for the variation of this focus for different materials, as well as to account for other factors, such as differences in the quality of input and output materials. We therefore used the PEF CFF as the basis for the EoL accounting for both vehicles and batteries.

For some of the materials a cut-off application is effectively used in practice where there is an even balance between use of secondary material in manufacturing and the EoL recycling rate. This suits the policymaker's viewpoint, since environmental burdens are mostly accounted for when they actually occur. An additional credit is effectively given only for materials used in vehicles and key powertrain

[50] Further information is available here: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

components (e.g. batteries, fuel cells) where the recycling rate (current or projected future rate) significantly exceeds the content of secondary material. This does justice to materials for which the automotive sector is a net recycling/secondary material contributor on a per-vehicle basis. Applying the PEF CFF formula in this case also accounts for allocation aspects and differences in quality between virgin and recycled materials. This largely ensures a robust and conservative approach which suits the policymaker's viewpoint, since environmental burdens are accounted for when they actually occur. Additionally, the approach does justice to materials for which the automotive sector is a net recycling contributor.

In the simplified hybrid approach, emission factors for materials with an average share of recycled material are used and an additional credit is given at the end-of-life based on the *difference* between the recycled content and the total recycling rate. For example, for a vehicle manufactured in 2020, the following formula is applied, illustrated in Figure A42 with an indication of additional PEF CFF elements:

Recycling Credit (in Year 2035) for Material A. = (Recycling Rate % – Recycled Content %) * (EF Virgin Material A – EF Recycled Material A) in Year 2035

Where, EF = emission factor

A complete summary of the PEF CFF is provided in the following Figure A43, with further details on the application of this formula provided in the PEF documentation (JRC, 2018a). For the purposes of our study, the parameters values used for different materials based upon PEF default values, or typical recycled content and recycling/recovery rates for vehicle/battery manufacturing and end-of-life disposal.

Figure A42: Schematic explanation of the simplified hybrid approach and additional factors included in the PEF Circular Footprint Formula (CFF)

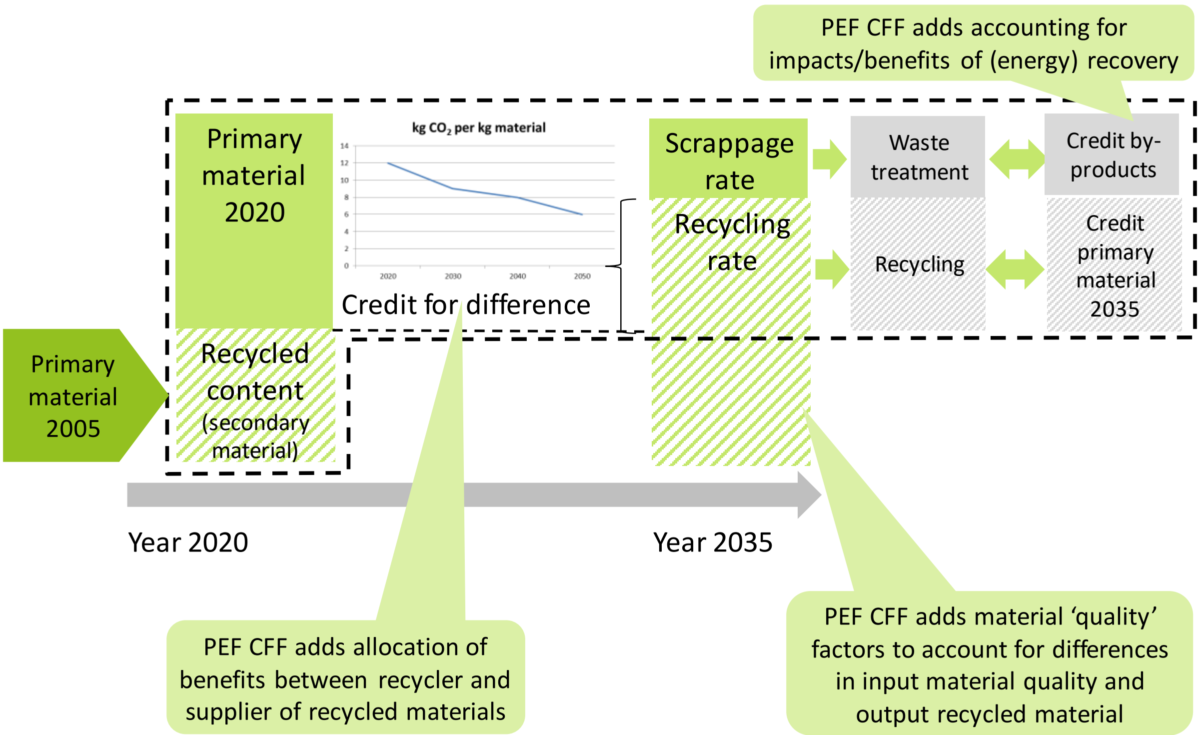


Figure A43: PEF Circular Footprint Formula definition: overall formula (CFF) and modular form (CFF-M)

material
$$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_P}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E^*_V \times \frac{Q_{Sout}}{Q_P}\right)$$

energy
$$(1-B)R_3 \times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}\right)$$

disposal
$$(1-R_2-R_3) \times E_D$$

Production burdens
$$(1-R_1)E_V + R_1 \times E_{recycled}$$
Cradle-to-gate

Burdens and benefits related to secondary materials input
$$-(1-A)R_1 \times \left(E_{recycled} - E_V \times \frac{Q_{Sin}}{Q_P}\right)$$

Burdens and benefits related to secondary materials output
$$(1-A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$$

Energy recovery
$$(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

Disposal
$$(1-R_2-R_3) \times E_D$$

Additional information from the EoL stage

Source: Formulae are taken from (JRC, 2018a), where further information is available on their application also.

Notes: The parameter definitions from the PEF CFF and CFF-M are summarised below

PEF CFF Parameter Definitions

A: allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes: it applies both to burdens and credits.

Qs_{in}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

Qs_{out}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Q_p: quality of the primary material, i.e. quality of the virgin material.

R_1: **proportion** of material in the input to the production that has been **recycled from a previous system**.

R_2: **proportion** of the material in the product that **will be recycled** (/reused) in a subsequent system (including inefficiencies in collection/recycling/reuse).

R_3: **proportion** of the material in the product that is **used for energy recovery at EoL**.

$E_{recycled}$ (E_{rec}): specific emissions and resources consumed (per unit of analysis) arising from all processes for the recycling (or reuse) of the material.

$E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per unit of analysis) arising from all processes for the recycling of the material at EoL.

E_v: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.

PEF CFF Parameter Definitions

E^*_V: specific emissions and resources consumed (per unit of analysis) arising from the virgin material to be substituted by recyclable materials.

EER: specific emissions and resources consumed (per unit of analysis) arising from the energy recovery process.

$E_{SE,heat}$; $E_{SE,elec}$: specific emissions and resources consumed (per unit of analysis) that would have arisen from the substituted energy source, heat and electricity respectively.

ED: specific emissions and resources consumed (per unit) arising from disposal of waste material at the EoL of the product, without energy recovery.

$X_{ER,elec}$; $X_{ER,heat}$: the efficiency of the energy recovery process for both heat and electricity.

LHV: Lower Heating Value of the material in the product that is used for energy recovery.

A3.8.2 EoL for used xEV batteries and sensitivities

Today the market for electric vehicle (xEV) traction batteries is fast growing and battery chemistries and energy densities as well as material composition are changing fast, too. Since most vehicles have a lifetime of more than 10 years and electric light duty vehicles (cars and vans) are just entering the mass market, recycling of used xEV batteries is not very significant today. Improved processes for xEV battery recycling are being developed, but the number of batteries being recycled is still fairly small. A huge increase in the number of used xEV batteries available for recycling can be expected for the future, making considerations for the end-of-life of batteries an issue.

The applied methodology for xEV batteries also takes into account potential future improvements in recycling and recovery rates for battery materials, and the change in energy mix used in battery recycling. As far as feasible other potential changes in recycling processes are also factored in, in a simplified way.

In addition to battery recycling, the repurposing of used xEV batteries for other applications (mainly anticipated for stationary energy storage) is often discussed. Since it is uncertain how many batteries will actually have a second life (e.g. in a stationary storage), second-life considerations are not generally included in detail in the overall life cycle assessment of current batteries.

To give an estimate of the possible emissions savings from re-using old xEV batteries, a sensitivity on battery repurposing/second-life was carried out. In agreement with stakeholder views, a credit has been applied which is based on the avoided use/displacement of an equivalent new energy storage battery (i.e. also as calculated in the modelling). The lifetime of the batteries during their first and second usage, as well as possible demand for used car batteries have been taken into account, and this results in in a fraction of a new battery being displaced on average for each xEV battery produced.

The calculation of this credit is summarised as follows (for the year 2035 as an example):

$$\text{Battery Second Life Credit (in Year 2035)} = \%\,EoL_{Batt} * \%Life_{NewBatt} * \%SOH_{EoLBatt} * Impact_{NewBatt\ in\ Year\ 2035}$$

Where,

$\%\,EoL_{Batt}$ = the average % share of all vehicle EoL batteries that are repurposed to replace new batteries

$\%Life_{EoLBatt}$ = the expected remaining lifetime (in years) of a second life battery as a % lifetime of new batteries

$\%SOH_{EoLBatt}$ = the remaining battery %SOH (State-of-Health) at the end-of-life in the vehicle

$Impact_{NewBatt}$ = the impact from manufacturing a new battery in 2035

A3.9 Impact categories

A3.9.1 Indicators

Life-cycle inventories (LCIs) often operate with thousands of substances. Some of these substances are understandable and instructive as such and are sometimes also stated as simple values. Examples are CO_2 emissions or particulate matter and NOx emissions in assessments of transport (especially Well-to-Wheel studies). Nevertheless, due to the large amount of substances frequently included in LCIs, impact categories are commonly used to enhance understanding and evaluate the magnitude and significance of the potential environmental impacts caused by a product. Thus, the inventory data is grouped and weighted according to potential damages. Weighting thus emphasises the contribution of particular components over others, e.g. by assigning Methane a much higher global warming potential than CO_2. Generally, endpoint indicators and midpoint indicators are distinguished in the reviewed literature (although some models, e.g. GREET, and assessments consider individual pollutant emissions only):

- **Endpoint indicators** directly refer to an impact in the field of human health, natural environment or resource consumption and most closely reflect the protected good. A common example is the assessment of life-years lost in respect to human health (e.g. DALYs (disability adjusted life years lost)).
- **Midpoint indicators** are weighting substances with similar effects along their mechanisms into an impact indicator via characterization factors. The impacts, however, may affect different endpoints (e.g. human health AND natural environment). It is important to understand that only potential impacts are quantified, while the actual end point damages may also be depending on other factors.

It is apparent that most evaluated literature uses midpoint indicators, though some studies also report only individual pollutant emissions, e.g. where they are particularly relevant to regulatory compliance / emissions reporting for particular pollutants. Even though endpoint indicators are described to be better understandable in their potential damage, it is noted that high uncertainties are associated with the translations from midpoint mechanisms into actual endpoint damages. Furthermore, midpoint effects are regarded as closer to actual policy making beyond constitutional definitions of protected goods.

For reasons of robustness and appropriateness for policy making, it was decided to base the impact assessment on commonly established midpoint indicators instead of more aggregated endpoints.

A3.9.2 Impact categories

The core impacts analysed in the study were defined by the Commission’s specification for the study:

- Greenhouse gas emissions
- Acidification
- Eutrophication
- Human toxicity
- Eco-toxicity
- Resource consumption.

Beyond these core impacts, which are critically discussed below, the scope of considered impact categories was widened with the intention of facilitating a critical discussion at the final stage of the project.

Though requested by the commission, the impact categories of **human and eco-toxicity** are hotly disputed due to the following reasons (see (ifeu, 2016) for further details):

- The number of effective substances is virtually infinite (in contrast to the scarcity of substances with available LCI data in practice).
- Impacts are highly diverse and can hardly be merged into one indicator.
- Toxic effects need exposition (spatial relation), while LCA data are typically not regionalised.

Currently, the USEtox approach is one of the most prominent models trying to tackle these challenges and is therefore suggested to cover these impacts in this study as requested by the commission.

USEtox is also endorsed by the UNEP/SETAC Life Cycle Initiative for characterising human and ecotoxicological impacts of chemicals and it is also the preferred approach of the ILCD handbook.

Nevertheless, transparency and data consistency have to be critically discussed since inventory data is often asymmetric and does not allow for a reasonable comparison. In order to avoid over-interpretations in comparative life-cycle assessments, the evaluation must therefore critically discuss both data completeness and data symmetry at the life-cycle balance sheet and analyse the results quantified in the impact assessment against the background of a meaningful significance threshold. This requires careful analysis of the records imported from databases.

An additional focus on **particulate matter formation** (PMF) was therefore identified as useful, as it includes the most relevant toxic air effects (see (ifeu, 2016)). Epidemiological studies have shown a correlation between the exposure to particulate matter and the mortality from respiratory diseases as well as a weakening of the immune system. PMF covers effects of fine particulates with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) emitted directly (primary particles) or formed from precursors as NOx and SO_2 (secondary particles). Thus, the most disputed tailpipe emissions of combustion engine vehicles are reflected in this indicator.

Furthermore, **ionising radiation** is included in the study. In some European countries nuclear power takes a significant share within the national electricity mix and is thus also represented within the EU electricity mix. While emissions of greenhouse gases and other air toxics are low, nuclear power is related with the discharge of radioactive nuclides from mining, fuel rod-production, power stations, reprocessing and final deposition. A further significant exposition has to be assumed from recycling of steel and concrete from dismantled power plants for construction, but is currently not considered in the ifeu electricity model due to lack of robust data.

The resource efficiency angle, or the prudent **consumption of natural resources**, has advanced to become a significant feature of the political agenda at the European Union level. Associated strategic papers outline the framework that includes environmental aspects, yet distinctly exceeds the environmental scope. The consideration of resources may thus be seen as supplementary information to the environmental analysis.

The literature review shows that the quantification of resource consumption currently is most commonly undertaken with the abiotic depletion potential. This approach considers the scarcity of material as a function of natural reserves related to the extraction rate. Only abiotic resources are considered and weighted as Antimony equivalents (Sb). This approach, however, is rather economically motivated and connected to social-economic policies instead of reflecting environmental impacts. Due to the international acceptance and lack of alternatives it is nevertheless used in this study.

To complete the resource consumption picture, the life cycle **cumulative energy demand (CED)** was used and differentiated by renewable, fossil and nuclear energy.

The category of land use is an important one, in particular when the scope includes biofuels. But other land covering renewable energies (e.g. PV or CSP) and also mining of metal ores shouldn't be neglected. Accounting for the land occupation (m^2) is often used, but does not provide information on the natural quality of the occupied area or about land-use change and the quality of the land before starting the use for transport that is under assessment. Nevertheless, land occupation was finally used in this study since it is easy to interpret and can in a second step also be combined with issues of soil quality or land use change for biofuels. Additionally, some aggregated inventory results including the main greenhouse gases, air pollutants and energy demand are given. The following individual air pollutant emissions are also tracked and reported: CO_2, CH_4, N_2O, NH_3, NOx SOx, PM_{10}, $PM_{2.5}$, and NMVOC, based upon their regulatory significance for transport[51].

A3.9.3 Impact assessment indicators

The basis for choosing the appropriate impact assessment methodologies has been the PEF guide, the suggested impact categories here have been regarded as a default option. However, in some cases different indicators were chosen, this concerns eutrophication, acidification, particulate matter and land use. Table A11 gives an overview of impact categories which deviate from the PEF recommended defaults and a justification.

[51] https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-6

Table A11: Overview of impact categories deviating from PEF recommended defaults

Impact category	Indicator in PEF	Default source in PEF	Deviation for our study	Justification of deviation
Acidification	Accumulated Exceedance (AE)	Seppälä at al. 2006, Posch et al. 2008	CML 2001	The Accumulated exceedance concept is mixing midpoint with endpoint elements while for endpoint characterization not actual effects, but legal thresholds are referred to. A change of emission limits influences the characterization and outside Europe there is no fundament for the application.
Eutrophication aquatic (freshwater /marine)	P equivalents/ N equivalents	ReCiPe 2008	CML 2001	Like Acidification there is a mixture of midpoint with endpoint by applying a FATE-model. A global application is not given. We recommend to stay at midpoint CML method eutrophication potential.
Eutrophication (terrestrial)	Accumulated Exceedance (AE)	Seppälä at al. 2006, Posch et al. 2008	CML 2001	See acidification We recommend to stay at midpoint CML method eutrophication potential.
Particulate matter	Disease incidences	Fantke et al. 2016 in UNEP 2016	Particulate matter formation in PM2.5 eq	Due to mix of endpoint/midpoint we apply PMF (Particulate Matter Formation), PM10/ PM2.5 based on physio-chemical mechanisms (→ midpoint)
Land use	Soil quality index	LANCA (as in Bos et al., 2016)	Land occupation in m^2 *a	The LANCA approach result is 4 or 5 individual indicator values, which then stand next to each other somewhat abruptly. From applicants we heard that the result is not fit for interpretation It is only focused on soil quality for fertility. Nothing about biodiversity and natural quality, which is what we would assume for a land use indicator We propose to use a basic land-use indicator = m2*a and then in a second step add issues of soil quality or land use change for biofuels.

This leads to the list of considered impact categories and indicators summarised in Table A A12. Whenever more than one implementation of a certain method exists, the latest version from the ecoinvent 3.5 database was used to ensure consistency across all parts of the process chain.

The scope of impacts is applied to all life-cycle stages of the study including fuel production and electricity generation.

When addressing the impacts of biofuels not only land use (occupation) but also land use change (LUC) may play a crucial role for the overall environmental impacts. The impacts of LUC (including soil organic carbon emissions) are measured in CO2eq and therefore are included in the GWP score for crop cultivation.

Table A A12: List of impact categories for the study

Impact category	Indicator and unit	Original source
Climate change	Greenhouse gas emissions GWP100 in CO_2 eq	IPCC 2013
Energy consumption	Cumulative energy demand in MJ (fossil and renewable)	ecoinvent 3.5 (Bourgalt 2017)
Acidification	Acidification potential in SO_2 eq	CML 2001
Eutrophication	Eutrophication potential in PO_4^{3-} eq	CML 2001
Photochemical ozone formation	Photochemical Ozone Creation Potential POCP in NMVOC eq	ReCiPe 2008
Ozone depletion	ODP in R11 eq	WMO 2014
Ionising radiation	Ionising radiation potentials in U235 eq	Frischknecht et al. 2000
Particulate matter	Particulate matter formation in PM2.5 eq	De Leeuw 2002
Human toxicity, cancer and non-cancer	Comparative Toxic Unit for Human Health in CTUh	USEtox (Rosenbaum et al 2008)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems in CTUe	USEtox (Rosenbaum et al 2008)
Resource depletion - minerals and metals	ADP ultimate reserves in Sb eq	Van Oers et al. 2002
Resource depletion - energy Carriers	ADP fossil in MJ	Van Oers et al. 2002
Land use	Land occupation in m^2 *a	ecoinvent 3.5 (Bourgalt 2017)
Water scarcity	Scarcity-adjusted water use in m^3	AWARE 2016

A3.10 Methodology: Background LCI and data

While all foreground process are modelled in detail for the study (partially taking into account unit-process datasets from different studies or pre-existing databases), for background data (especially on the material chains) an LCI background database is used.

To ensure consistency between the different lifecycle stages, it was decided to take all background data from the same LCI database, as far as this was possible. Only where the database lacked good quality data for a relevant background material/process, was a different source based on the project team's own assessment or an (adapted) dataset from another database.

Currently, there are three main databases that are widely used throughout the LCA community: the ecoinvent database, the GaBi database and (for transport based LCAs) the US GREET model:

- The **ecoinvent** database is provided by the Swiss non-profit ecoinvent association and supplies well documented unit-process datasets for a huge variety of different products. Even though the ecoinvent database is updated regularly, some datasets contained are older or are based on a smaller number of samples.

- The **GaBi** database is supplied by thinkstep and offers a large number of datasets for different products. It includes just one system model, which is attributional and has a large share of industry data. However, GaBi only supplies aggregated datasets making transparency and adaptability of datasets an issue.
- **GREET** (Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model) is maintained by US Argonne National Laboratory. It supplies the life cycle emissions for various vehicle and fuel combinations in the US including vehicle manufacturing and energy provision. However, GREET is not a full LCI database, because its scope is limited to certain air pollutants, energy and greenhouse gases.

The main differences between the databases have been assessed and are shown in Table A13.

Table A13: Comparison of different background databases

	ecoinvent 3	GABI	GREET
System model	Consequential and attributional (cut-off and APOS)	Attributional	Attributional
Scope	Complete LCI database including all relevant sectors and with worldwide datasets	Complete LCI database including all relevant sectors and with worldwide datasets	LCI Database with a focus on the transport system in the US (including vehicle manufacturing and energy provision)
Availability in LCA software	openLCA Umberto LCA+ SimaPro GaBi (only system processes)	openLCA Umberto LCA+ GaBi	GREET 2
Transparency	Documentation in datasets and in reports	Documentation in datasets and in reports	Documentation in reports
Adaptability of datasets	Unit-process datasets	Aggregated datasets	Partially aggregated datasets
Coverage of impacts	Resources, emissions to air, water and soil	Resources, emissions to air, water and soil	Energy consumption, greenhouse gases and air pollutants

Since a complete lifecycle assessment covering a wide range of different impact categories was to be carried out, only databases covering all relevant elementary flows were considered for the primary source. Therefore GREET was ruled out as a primary background database, however this dataset was useful to help fill key data gaps, and to provide data for the foreground system (particularly for battery manufacturing and recycling processes), that have been adapted to the study methodology (e.g. also adjusting to European conditions, where relevant).

Both ecoinvent and GaBi are widely used databases throughout the LCA community with a good data quality and a wide coverage of processes and emissions.

However, it was important for the study to vary certain background processes and to gain further insights into the unit-processes. Here the ecoinvent database is better suited, due to the more aggregated (and often confidential) datasets in the GaBi database. Furthermore, ecoinvent provides different system models and gives the possibility to choose between an attributional and a consequential database.

Therefore the ecoinvent (in its latest version 3.5 cut-off) was used for the majority of the background data, except where gaps or quality issues were identified. In such cases, data mainly from the GREET model was used to update these processes (see Appendix A4 for further information).

A3.10.1 Projecting future impacts from materials used in vehicle manufacturing

The impacts from producing materials used in vehicle production are expected to reduce significantly in the future, through to 2050, due to improvements in process efficiency and shifts in the generation mix used to supply energy for the processing/production of raw materials. This improvement is being driven by long-term global objectives to mitigate potential climate change.

The relative future changes in the impacts from production of these materials will be different for different impact categories and for different materials. This reflects differences in the significance of different impacts at different stages of the material production lifecycle, including also the significance of process electricity consumption (which is very high for certain key materials like aluminium).

Under our developed methodology, the underlying ecoinvent 3.5 (cut-off) datasets for key materials have been adapted to account for these potential improvements through two principal means:

1) ***For steel and aluminium:***
   a) *GHG emission impacts*: future projected improvements in the GHG intensity of primary and secondary steel and aluminium production are based upon analysis by the IEA (which factors in both process improvements and decarbonisation of process electricity).
   b) *Other impacts*: based on the proportion of impacts due to process electricity consumption, and future projections in reduction in global average electricity production impacts.
2) ***For other materials***: based on the proportion of impacts (for different materials and impact categories) due to process electricity consumption, and future projections in reduction in global average electricity production impacts.

In order to calculate the potential future reductions in impacts due to process electricity use, data on the process electricity consumption for each material was extracted from the background database.

This process electricity data was used together with future trends in the impact intensity of global (or regional) electricity supply (as output from the electricity production chain calculations) to estimate projections for all materials used in vehicle manufacturing across all impact categories.

A similar approach was also applied to account for future changes in the impacts of secondary material processing – i.e. used to define the credits for end-of-life recycling of key materials which will usually occur 10-15 years after the manufacturing of the vehicle. This is discussed further in Section A3.13.4.

A3.11 Methodology: Electricity production chains

For electricity generation, a wide array of different technologies are deployed, which may differ between countries and regions, as well as over time. Moreover, in order to adequately cover the environmental burdens associated with electricity generation, all lifecycle stages ("cradle to grave"), including all relevant upstream processes and EoL (end-of-life) treatment, are included. Table A14 summarises the methodology developed and applied for this project.

As part of this project, detailed and consistent outputs were needed for individual electricity production chains, and for a variety of regional and country generation mixes. In addition, there was a need to also account for improvements in the average technical efficiency of installed generation capacity in the EU in future years, and consistency as far as feasible with EC modelling scenarios. Whilst information is available in Ecoinvent for individual country electricity production chains, and generation types, it was not possible to readily fulfil the other criteria in a systematic way for this project. For this reason ifeu's Umberto model was selected to develop relevant outputs in a consistent way. Further information on the Umberto model basis and background data is provided in Appendix Section A4.2.1.

Outputs for different electricity chains are based on a combination of results derived from ifeu's Umberto electricity modelling for different generation types, and scenario projections for electricity (generation mix, efficiency, losses, etc) for different EU countries based on two EC energy modelling scenarios (Baseline and Tech1.5). For non-EU countries (Canada, Japan, Korea and USA) and for a world average grid mix, modelling was based mainly on publicly available IEA ETP modelling scenario datasets[52].

[52] IEA Energy Technology Perspectives 2017, available here: https://www.iea.org/etp/etp2017/secure/, https://webstore.iea.org/energy-technology-perspectives-2017

Table A14: Summary of the methodology applied for electricity chains

Data type	Summary of the applied methodological proposal
General methodological approach	• LCA with a PCA (process chain analysis)* approach comprising all life cycle stages involved ("cradle to grave"); for the countries in focus modelling of all significant generation technologies on a generic basis with supplementing additional country/technology-specific parameterisation; • Adjustment of choice of electricity generation composition based on EC energy system modelling scenarios: a Baseline scenario and a decarbonisation scenario (Tech1.5); • For electricity: Average consumption mix of country of origin or EU average mix; output as low voltage electricity.
Coverage of electricity generation types and fuel types	All relevant (> 5% share) or significant (>5% impact on results across impact categories) technologies / fuels for all spatial / temporal situations. For example, these would at least include conventional thermal power generation (i.e. with the fuel types below) with/without carbon capture and storage (CCS) where appropriate, as well as wind, solar and hydro power generation.
Fuels for electricity generation	• Coal (hard coal, lignite) • Fuel Oil • Natural Gas • Nuclear fuels (oxidic) • Waste • Solid biofuels • Liquid biofuels • Biogas / Bio methane
Generation efficiency	Technology-specific considerations and country-specific considerations. Conversion efficiency based on EC PRIMES modelling scenario outputs for different countries / EU28 as a whole (two high-level scenarios: Baseline and Tech1.5.
Losses	Losses associated with grid integration, transmission, and distribution, based on data from EC PRIMES modelling for the EU (two high-level scenarios: Baseline and Tech1.5), and IEA modelling for non-EU regions, with conversions between Low / Medium / High voltage (e.g. for electricity used in industrial-scale processes) based on data from ecoinvent, see Table A15.
Imports/Exports	Included for all countries based on EC modelling datasets
Generation plant production	Included in accordance with general cut-off criteria
Other elements	• Avoidance of double counting • Technology-specific constraints (e.g. generation profile, phase-out of nuclear energy) are accounted for in the EC/IEA scenario datasets.
Temporal considerations	The current (2020) situation is used as a baseline with robust assumptions regarding future developments and corresponding projected future mixes. These future projections are based on EC modelling scenarios (for the EU), and datasets from the IEA (for non-EU regions – CN, JP, KR, US, World).
Spatial considerations	All countries under scope and additional countries that have relevant contributions to the supply chain for all relevant direct (import of electricity) and indirect flows (i.e. as indicated above).
Data sources	Openly accessible data from e.g. EC energy modelling, IEA, EUROSTAT; LCA databases, e.g. ecoinvent or BioEM for background system modelling.

Notes: * Process chain analysis (PCA) assesses every step of a process chain individually, presenting a bottom-up view that results in greater and more complex efforts for data collection than simple input-output analysis (IOA).

Table A15: Summary of regional average factors for conversion of electricity impacts between Low / Medium / High Voltage grids, as utilised in the modelling for vehicle and battery manufacturing

Region for	To convert	Multiply by:	
Electricity	**impacts in units of**	**Low Voltage to Medium Voltage**	**Low Voltage to High Voltage**
EU28	kg[impact]/kWh	96.9%	95%
World	kg[impact]/kWh	94.3%	94%
US	kg[impact]/kWh	95.5%	94%
CN	kg[impact]/kWh	96.1%	95%
JP	kg[impact]/kWh	96.3%	96%
KR	kg[impact]/kWh	97.6%	97%

Source: Calculated by Ricardo from exported impact data from ecoinvent

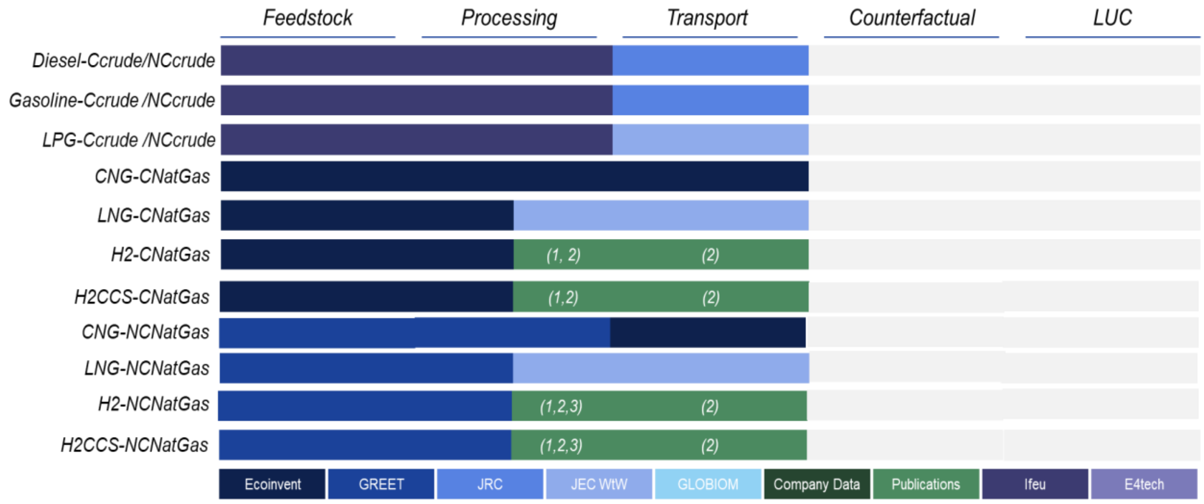
A3.12 Methodology: Foreground data for fuel production chains

This section provides further details on the foreground data used in the Fuels Module to model the 60 fuel chains. The figure in each subsection outline the sources used in each fuel chain along with which part of the chain they contribute to.

A3.12.1 Foreground data: fuels from primary fossil feedstocks

Figure A44 shows the foreground data sources used to model fuels from primary fossil feedstocks. Initial methodological choices from the literature review and stakeholder consultation could not be implemented for practical reasons, which are detailed in Section 3.4.2.1.1 of the Main Report. As a result, crude oil extraction data from Ecoinvent was used in combination with the ifeu refinery model, covering both the feedstock and processing stages. The ifeu refinery model dataset was paired with JRC (2019) data for downstream transportation, storage and distribution of diesel and gasoline, while JEC (2014) was used for the downstream transportation, storage and distribution of LPG. For each end-fuel, only two different datasets were required to complete the fuel chain.

Figure A44: Foreground data sources for primary fossil fuel chains



(1) Suzmosas et al. (2013): SMR process
(2) DoE Technical Targets for Hydrogen Delivery Components: H2 compression, transport and distribution
(3) Koomneef J et al. (2008): CO2 storage

For conventional natural gas Ecoinvent datasets for natural gas production in Russia, Algeria and Germany were used. A weighted average data set was constructed, based on the gas mix as reported by thinkstep (thinkstep AG, 2017) where Germany in this case represents EU countries, Russia represents Russia and Algeria represents "other". The downstream transportation, storage and distribution of the CNG produced is taken from Ecoinvent. Therefore, other than the use of the NGVA report to calculate the gas mix, all data used to model CNG from conventional natural gas is taken from one dataset. For LNG from conventional natural gas, an additional source, JEC was required to model liquefaction of natural gas as well as the downstream transportation, storage and distribution of LNG. This liquefaction dataset was also used for the liquefaction of natural gas from unconventional natural gas as well as the liquefaction of biomethane and SNG derived from all feedstocks considered, providing consistency across the fuel chains. GREET was used to model the extraction and processing of non-conventional natural gas, with all stages in the fuel chain after processing modelled the same as with conventional natural gas. GREET was used as natural gas production from non-conventional natural gas is not available in the Ecoinvent dataset. However, utilising the same dataset for both would have been preferred as this would provide consistency between the fuel chains, allowing for more accurate comparisons between results to be made.

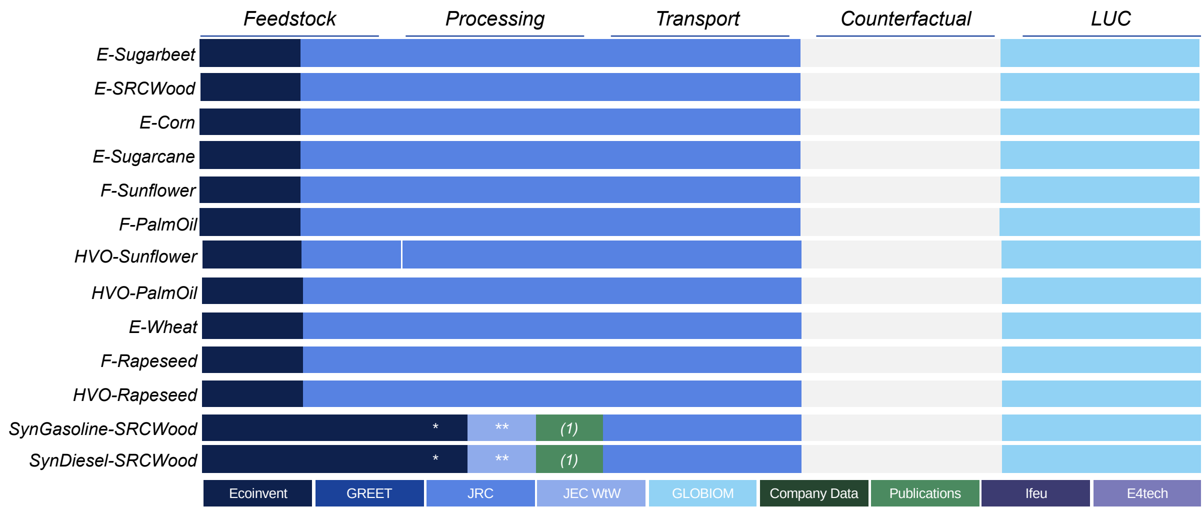
For the production of hydrogen from natural gas, the data used to model Steam Methane Reforming (SMR) is taken from a publication Suzmosas et al (2013). The downstream transport, distribution and storage of hydrogen data is taken from the DoE Technical Targets for Hydrogen Delivery Components. For liquid hydrogen, liquefaction data and downstream transportation, storage and distribution were taken from JEC (2018). An additional source for modelling the storage of CO_2 was required for the hydrogen production with CCS fuel chains. Koomneef J et al (2008) provided electricity input required to compress, transport and inject the CO_2 into geological storage. While it is understood this is a highly simplified model of CO_2 storage, due to the primary focus of the study being on LCA methodologies, more detailed modelling of CO_2 storage was not explored.

A3.12.2 Foreground data: fuels from primary biogenic feedstocks

As a result from the literature review and stakeholder consultation, data used to model the fuel chains of primary biogenic feedstocks was taken from JRC (2019) default values for RED II, with the exception of feedstock cultivation data which was taken from Ecoinvent and data to represent LUC taken from GLOBIOM, as shown in Figure A45. I Ecoinvent data were used for cultivation as they comprehensively cover field emissions and non-GWP impacts from agricultural operations (incl. infrastructure). Furthermore, N_2O emissions taken from GNOC were combined with the Ecoinvent datasets. For wheat and rapeseed fuel chains, additional drying which was not captured in Ecoinvent was required in the feedstock stages and was modelled using JRC data. As shown in Figure A45, the production of synthetic fuels from SRC wood differs somewhat from the other primary biogenic fuel chains, as it required three different sources:

- Ecoinvent: Gasification of woodchips to syngas
- JEC (2018): Fischer-Tropsch product slate and process efficiency
- Iribarren, D et al. (2013): Fischer-Tropsch inputs and outputs

Figure A45: Foreground data sources for primary biogenic fuel chains



(1) Iribarren, D et al. (2013): Fischer-Tropsch inputs and outputs
* Gasification to syngas
** Fischer-Tropsch product slate and overall FT process efficiency

A3.12.3 Foreground data: fuels from secondary biogenic feedstocks

In general, the number of datasets required to model complete fuel chains was higher for secondary feedstocks, shown in Figure A46, as the processes for producing fuels from secondary biogenic feedstocks are typically less commercially mature. Nonetheless, complete data sources which are representative of the EU were preferred, which is why the JRC/JEC datasets are favoured. Where this was not possible, other sources including literature and Ecoinvent had to be adopted.

Feedstock collection, transportation and pre-processing (e.g. drying) data was taken from the JRC default values for RED II. In the processing steps a number of additional data sources were required to complete the fuel chains. For example, to model the production of synthetic fuels from forestry residues, sawdust and agricultural residues, gasification data was taken from Ecoinvent, a Fischer-Tropsch product slate and process efficiency was taken from JEC (2018) and Fischer-Tropsch inputs and output flows (other than the products) were taken from a single peer-reviewed publication. For several of the less commercially mature fuel chains it was necessary to use single peer-reviewed publications for certain steps in the chain. Consequently these chains may be less representative of the average impacts for this fuel chain. As discussed in A3.12.1, liquefaction of biomethane was modelled based on the JEC (2018) dataset for liquefaction of natural gas. Downstream transportation, storage and distribution of the fuels was taken from the JRC where possible (ethanol, syndiesel, syngasoline, FAME and HVO). For biomethane and LBM the same transportation data as implemented for fossil methane (see section A3.12.1 is used). This was considered a proxy as the scale of biomethane liquefaction is likely to be much smaller than that of natural gas. Biomethane transportation was based on the transportation of CNG within the EU from Ecoinvent, whilst LBM transportation and distribution is based upon JEC (2018) distribution of LNG data, to account for the production of LBM being produced within the EU. Counterfactual data has been taken from a variety of sources in conjunction with internal modelling. Avoided emissions from secondary feedstocks were modelled using Ecoinvent data for the combustion of these materials. The impacts from the electricity used to replace them was taken from the electricity modelling within Module 2 of the tool. The counterfactual modelling is summarised in Table A16.

Figure A46: Foreground data sources for secondary biogenic fuel chains

(1) Iribarrren, D. et al. (2013): FT inputs and outputs (excluding FT products)
(2) Voet, E. et al. (2007): Electricity and heat from wheat straw by combustion in CHP (counterfactual scenario)
* Gasification to syngas
** FT product slate
*** CNG transportation (within EU) and distribution used as proxy
**** Liquefaction of LNG used as proxy
***** LNG distribution used to model transportation and distribution for LBM

Table A16: Counterfactual scenario modelled for each secondary biogenic feedstock

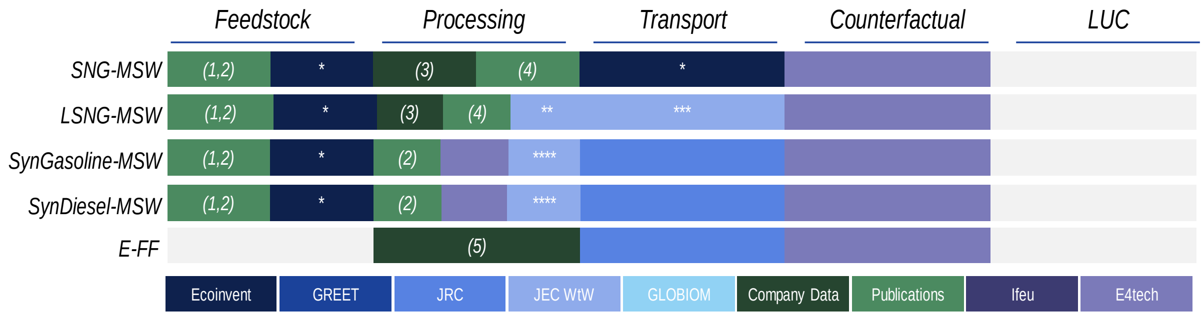
Feedstock	Avoided environmental impact	Counterfactual use modelled	Material / energy used to replace feedstock, when diverted from counterfactual use to fuel production
UCO	Incineration of UCO (Ecoinvent, edited)	Combusted to generate electricity (0.26$MJ_{electricity}/MJ_{UCO}$)	Grid electricity (ifeu model)
Straw	Incineration of waste wood (Ecoinvent)	Combusted to generate electricity (0.22$MJ_{electricity}/MJ_{straw}$)	Grid electricity (ifeu model)
Agricultural residues	Incineration of waste wood (Ecoinvent)	Combusted to generate electricity (0.22$MJ_{electricity}/MJ_{agricultural\ residues}$)	Grid electricity (ifeu model)
Forest residues	Incineration of waste wood (Ecoinvent)	Combusted to generate electricity (0.23$MJ_{electricity}/MJ_{forest\ residues}$)	Grid electricity (ifeu model)
Sawdust	Incineration of waste wood (Ecoinvent)	Combusted to generate electricity (0.23$MJ_{electricity}/MJ_{sawdust}$)	Grid electricity (ifeu model)
Manure	CH_4 and N_2O emissions released by manure left on fields (JRC and E4tech calculations)	Used on field as fertiliser	None (the digestate from AD can be applied to the field as fertiliser with comparable nutritional value as raw manure, given that nitrogen, phosphorus and potassium remain in the digestate.

Feedstock	Avoided environmental impact	Counterfactual use modelled	Material / energy used to replace feedstock, when diverted from counterfactual use to fuel production
			Therefore there are no additional emissions from having to provide fertiliser to the field in an alternative way)

A3.12.4 Foreground data: fuels from secondary fossil and mixed feedstocks

As with fuels from secondary biogenic feedstocks, those derived from secondary fossil or mixed (MSW) feedstocks were reliant on several, differing datasets, shown in Figure A47. For the production of ethanol from waste industrial gases (carbon monoxide), only one company is developing this technology therefore no cross-checks could be performed on this data. The fuel chains with MSW as a feedstock required a significant number of data sources for the feedstock and processing stages, the nature of which varied widely. As can be seen in Figure A47, the modelling of fuels produced from secondary fossil feedstock was more reliant on publications and data directly from companies than for the other fuel chains, highlighting the low commercial maturity of such chains. In most cases multiple data-sources were combined to provide foreground data for just one process step. For example, for the collection and pre-processing of MSW, three sources were used. The LHV of MSW was taken from Suresh et al. (2018), the biogenic content of the MSW was taken from Ecoinvent and the inputs required for the sorting of the MSW were taken from Pressley (2014). Background data for counterfactual impacts was taken from Ecoinvent, with calculations carried out by E4tech, based on industry data, as highlighted in Table A17.

Figure A47: Foreground data sources for secondary fossil and mixed fuel chains



(1) Pressley (2014): Sorting of MSW
(2) Suresh et al. (2018): LHV of MSW; Fischer-Tropsch
(3) Progressive Energy (2017): CO2 emissions from SNG production
(4) Kraussler et al. (2018): Inputs for SNG production
(5) Process data provided by Lanzatech
** Biogenic content of MSW; CNG transportation (within EU) and distribution used as proxy for SNG*
*** Liquefaction of NG used as proxy*
**** Distribution of LNG used to model transportation and distribution of LSNG*
***** FT product slate and overall FT process efficiency*

Table A17: Counterfactual scenario modelled for each secondary fossil/mixed feedstock

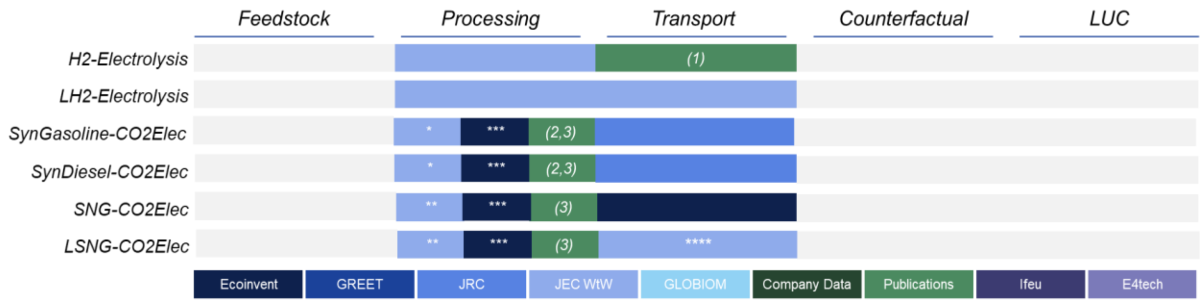
Feedstock	Avoided environmental impact	Counterfactual use modelled	Material / energy used to replace feedstock, when diverted from counterfactual use to fuel production
MSW	Incineration of MSW (Ecoinvent)	Combusted to generate electricity ($0.23MJ_{electricity}/MJ_{MSW}$)	Grid electricity (ifeu model)

Feedstock	Avoided environmental impact	Counterfactual use modelled	Material / energy used to replace feedstock, when diverted from counterfactual use to fuel production
Waste industrial gas	Flaring of CO (E4tech calculations)	Combusted to generate electricity ($0.26 MJ_{electricity}/MJ_{waste\ industrial\ gas}$)	Grid electricity (ifeu model)

A3.12.5 Foreground data: e-fuels

Given the early stage of commercialisation, synthetic fuels and (L)SNG derived from electricity required several datasets to be used, as shown in Figure A48. However, the production of hydrogen and liquid hydrogen through electrolysis are well documented in the JEC data set, as well as liquefaction, transport, storage and distribution of liquid hydrogen. As for hydrogen produced from primary fossil feedstocks, DoE Technical Targets for Hydrogen Delivery Components was used for the downstream hydrogen transport and distribution. Note, the H2-ElectroysisRE chain was not include in Figure A48, as the foreground data is identical to the H2-Electrolysis fuel chain, the difference between the two arising only from which electricity scenario is considered.

Figure A48: Foreground data sources for e-fuel chains



(1) DoE Technical Targets for Hydrogen Delivery Components: H_2 transport and distribution
(2) Schmidt et al. (2018): Process efficiency and water requirement for FT process
(3) Frischknecht, R. (1999): electricity input for CO_2 purification
** FT product slate*
*** H_2 and CO_2 inputs (and liquefaction of SNG for LSNG-CO2Elec)*
**** CO_2 purification (heat and MEA inputs)*
***** LNG distribution used to model transportation and distribution for LSNG*

A3.12.6 Foreground data: robustness and limitations of data and assumptions

Table A18 provides the list of all 60 fuel chains from the fuel chains module, along with a description of the robustness of the data and assumptions used in the modelling (source, quality, impacts on results, etc.) and any additional comments. As with all LCA studies, the results of this study should always be considered within the context of the goals of the study, methodology and data-sources used. Where the robustness of data has been deemed of a very low standard (highlighted red in the table), results are not considered sufficiently robust for publication and have not been included in the Results Viewer provided to the Commission as an output from this study (see Section 4.6 in the main report). Furthermore these fuel chains have not been included in the fuel blends developed for use in the overall vehicle results. Results for chains where there is some concern over the robustness of the data or assumptions (highlighted amber in the table) have been published in the Results Viewer supplied to the Commission but should be treated with a degree of caution. In making use of these results, if comparisons are made between primary fossil fuels and other fuel chains, then the set of results which apply common methodological choices across the fuel chains should be used, i.e. energy allocation.

In general, it was necessary to use less robust data for those fuel chains which are at earlier stages of commercialisation. In addition, the use of counterfactual scenarios and substitution methodology, required the use of some less robust data and assumptions. As discussed throughout this report, it is difficult to accurately model counterfactual scenarios. A simplified approach was taken assuming just one counterfactual use per feedstock. Further, the substitution methodology taken to address multifunctionality required an assumption to be made on what is the displaced product(s) and how much does one unit of the co-product displace. It was assumed that each co-product only displaced one product and that it replaced it on a 1:1 basis (mass basis for non-energy co-products and energy basis for energy co-products).

Many of these chains relied predominantly upon datasets which were constructed for a GHG assessment, e.g. JRC and JEC datasets. Therefore, while it likely captures all GHG relevant inputs and outputs, it is also possible that some inputs/outputs, which have less of an impact on GHG scores, were not captured.

Table A18: Overview of fuel chains modelled in Module 3 of the LCA calculation framework and level of robustness of data used and related assumptions

Feedstock	End fuel	Robustness of data used	Robustness of assumptions	Limitations of modelling	Comments	Included in Results Viewer
Conventional Crude	Diesel	Ecoinvent used for extraction data (2007). ifeu's refinery model used.	Assumptions taken within ifeu's refinery model.	Results are only available using an energy allocation approach. Other fuel chains have been modelled using both an energy allocation and substitution approach. Therefore, when comparing these fuel chains to others, results of the other fuel chains should always be based on an energy allocation.	Findings in line with CONCAWE model used in JEC for conventional crude chains.	✓
	Gasoline					✓
	LPG					✓
Non-conventional Crude	Diesel	ifeu's refinery model used with increased share of non-conventional but same Ecoinvent data used for extraction as for conventional			Specificities of non-conventional extraction not entirely captured	✕
	Gasoline					✕
	LPG					✕
Conventional Natural Gas	CNG	Ecoinvent data – representative EU mix	JEC (2018) used to model liquefaction step, as well as transportation, storage and distribution	One substitution scenario modelled for co-products. In this case, the only co-product is sulphur, which is substituted on a 1:1 basis with conventional sulphur production.	Findings in line with JEC (2018)	✓
	LNG				Findings in line with JEC (2018)	✓
	Hydrogen (SMR)	SMR data based on peer reviewed literature. Transportation data from US DoE.				✓
	Hydrogen (SMR w CCS)		Associated impacts of Amine solvent consumption for carbon capture are not modelled.			✓
Non-conventional Natural Gas	CNG	Data represents US shale gas (GREET), not EU. SMR data passed on peer reviewed literature.			CNG- Comparison with JEC (2018) shows discrepancy likely due to GREET data	✓
	LNG					✓
	Hydrogen (SMR)					✓

Feedstock	End fuel	Robustness of data used	Robustness of assumptions	Limitations of modelling	Comments	Included in Results Viewer
	Hydrogen (SMR w CCS)	Transportation data from US DoE.	Associated impacts of Amine solvent consumption for carbon capture are not modelled.		using US Shale and JEC using EU shale LNG – no results available in JEC (2018), so no comparison possible	✓
Municipal Solid Waste	Synthetic Gasoline	Different datasets use for pre-processing of MSW, processing into fuel, and fuel product slate (in the case of syndiesel and syngasoline production) Few data sources for cross-referencing.	Data adjusted where possible to account for variable characteristics of MSW between different sources. CO_2 emissions directly from processing had to be estimated.	Only one counterfactual scenario modelled. For co-products, only one substitution scenario modelled.		×
	Synthetic Diesel					×
	SNG					×
	LSNG					×
Sugar beet	Ethanol	Cultivation data from Ecoinvent. Land-use change data from GLOBIOM and SOC/N2O emissions from GNOC.	LUC impacts given on a per MJ of final fuel basis, not taking into account different processes to produce these fuels.	For co-products, only one substitution scenario modelled.	Amortization of LUC emissions over 20 years. No attempt to model longer amortization period (e.g. 100 years).	✓
Sugarcane	Ethanol					✓
Corn	Ethanol					✓
Wheat	Ethanol					✓
SRC Wood	Ethanol					✓
	Synthetic Gasoline	FT synthesis based on JEC and a single peer reviewed source	Process efficiency and product slate taken from JEC, whilst other inputs and output taken from single peer reviewed literature.			✓
	Synthetic Diesel					✓
Agricultural Residues	Ethanol	Data from JRC RED II default values (straw pellets)		Only one counterfactual scenario modelled. For co-products, only one		✓

Feedstock	End fuel	Robustness of data used	Robustness of assumptions	Limitations of modelling	Comments	Included in Results Viewer
	Synthetic Gasoline	FT synthesis based on JEC and a single peer reviewed source	Due to lack of publicly available data – FT stage modelled on syngas from wood biomass	substitution scenario modelled.		×
	Synthetic Diesel					×
	Biomethane (AD)	Data from JRC				✓
	Liquid Biomethane (AD)	Data from JRC	Liquefaction of natural gas used as proxy.			✓
	Biomethane (Gasification)	JRC and Ecoinvent data				✓
	Liquid Biomethane (Gasification)	JRC and Ecoinvent data	Liquefaction of natural gas used as proxy.			✓
Forestry Residues	Ethanol	Data from JRC RED II default values		Only one counterfactual scenario modelled. For co-products, only one substitution scenario modelled.	Data and assumptions sufficiently robust but the weight of counterfactual is really massive.	✓
	Synthetic Gasoline	FT synthesis based on JEC and a single peer reviewed source	Process efficiency and product slate taken from JEC, whilst other inputs and output taken from single peer reviewed literature.			✓
	Synthetic Diesel					✓
	Biomethane (Gasification)	JRC and Ecoinvent data				✓
	Liquid Biomethane (Gasification)	JRC and Ecoinvent data	Liquefaction of natural gas used as proxy.			✓

Feedstock	End fuel	Robustness of data used	Robustness of assumptions	Limitations of modelling	Comments	Included in Results Viewer
Saw Dust	Ethanol	Data from JRC RED default values		Only one counterfactual scenario modelled. For co-products, only one substitution scenario modelled.		✓
	Synthetic Gasoline	FT synthesis based on JEC and a single peer reviewed source	Process efficiency and product slate taken from JEC, whilst other inputs and output taken from single peer reviewed literature.			✓
	Synthetic Diesel					✓
	Biomethane (Gasification)	JRC and Ecoinvent data				✓
	Liquid Biomethane (Gasification)	JRC and Ecoinvent data	Liquefaction of natural gas used as proxy.			✓
Manure	Biomethane (AD)	JRC RED II default values		Counterfactual scenario modelled is in line with JRC's commentary on CH_4 and N_2O emissions	Avoided methane emissions represent a significant discount over GHG emissions.	✓
	Liquid Biomethane (AD)	JRC RED II default values	Liquefaction of natural gas used as proxy.			✓
Waste Industrial Gas	Ethanol	Data provided by the company leading the development of this process, cannot be cross checked		Counterfactual scenario based on a carbon balance to calculate avoided CO_2 produced through combustion of CO (complete combustion assumed). For co-products, only one substitution scenario modelled.		✕
Rapeseed	FAME	Cultivation data from Ecoinvent. Land-use	LUC impacts given on a per MJ of final		Amortization of LUC emissions over 20 years. No	✓
	HVO					✓

Feedstock	End fuel	Robustness of data used	Robustness of assumptions	Limitations of modelling	Comments	Included in Results Viewer
Sunflower	FAME	change data from GLOBIOM and SOC/N_2O emissions from GNOC.	fuel basis, not taking into account different processes to produce these fuels.	For co-products, only one substitution scenario modelled.	attempt to model longer amortization period (e.g. 100 years).	✓
	HVO					✓
Used Cooking Oil	FAME	JRC RED II default values		Counterfactual scenario based on mineral waste oil, GWP impact value set to GWP_B and GWP set to zero to account for biogenic nature of UCO. For co-products, only one substitution scenario modelled.	Findings in line with JEC (2018)	✓
	HVO				Findings in line with JEC (2018)	✓
Palm Oil	FAME	Cultivation data from Ecoinvent. Land use change data from GLOBIOM and SOC/N2O emissions from GNOC.	LUC impacts given on a per MJ of final fuel basis, not taking into account different processes to produce these fuels.	For co-products, only one substitution scenario modelled.	Amortization of LUC emissions over 20 years. No attempt to model longer amortization period (e.g. 100 years).	✓
	HVO					✓
Electricity	Hydrogen	Combined data from JEC and US DoE	Only one transport scenario modelled		Combination of US and EU data makes results less consistent. Result viewer allows user to choose grid or 100% RE. Improved comparability	✓
	Liquid Hydrogen					✓
Electricity + CO_2	Synthetic Gasoline	Several data sets required to model one life-cycle stage. No commercial-scale operating plants.	Several assumptions were required due to the number of datasets used.	A counterfactual for CO_2 is not explicitly modelled, as it is assumed that the avoided CO_2 emissions would exactly cancel out CO_2 emissions from fuel combustion		✓
	Synthetic Diesel					✓
	SNG					✓
	LSNG					✓

A3.13 Methodology: Vehicle cycle

The vehicle cycle is subdivided into the following four aspects, which are discussed in turn below in the following sections. Due to the significance of impacts from battery manufacturing (and recycling), this has been treated in more detail and is summarised in a final section:

1. *Vehicle specifications*: key characteristics of the vehicles (and powertrains) analysed that feed into the calculation of impacts from the vehicle production, operation and end-of-life stages.
2. *Vehicle production*: impacts resulting from the materials and processes used in the manufacturing of vehicles and key components.
3. *Vehicle operation*: key parameters determining the operational (use) phase of the vehicle, including energy consumption, direct emissions, lifetime activity profiles and maintenance.
4. *Vehicle end-of-life*: accounting for recycling and disposal of the vehicle / key components, potentially with additional accounting for reuse/repurposing of xEV batteries.

Further information on the specific datasets and a selection of the key assumptions/input data used in the vehicle cycle calculations is also provided in Appendix A4.

A3.13.1 Vehicle specification

The key parameters used to characterise and define the vehicles (and powertrains) included in the LCA are summarised in Table A19, with further details provided in the subsections below on how they were defined in the LCA calculations.

Table A19: Key parameters for vehicle specification

Data / parameter type	Summary description
General vehicle specifications	A range of characteristics / specifications for different vehicle types have an influence on the vehicle's composition, manufacture and operational energy consumption and emissions. For example, peak engine/motor power requirements, (electric or other fuel) range requirements, body type / configuration, auxiliary power demands.
Vehicle unladen mass and composition	Different vehicle types have different unladen masses and material composition. The overall mass of the vehicle influences the operational energy consumption, and the scale of the impacts from the manufacture of materials used in the vehicle. Different materials may be utilised to achieve vehicle mass reduction, and components for alternative powertrains have different composition to those for conventional ICEVs.
Energy storage and fuel cells	The type and size / specification of energy storage (i.e. electric traction battery, hydrogen, CNG or LNG storage tanks) and fuel cells.

A3.13.1.1 General vehicle specifications

The modelling of different generic vehicle types, segments and powertrains (as outlined in earlier Section A3.4.1) is based on information on primary conventional reference vehicle/powertrain types, and the use of scaling factors and market / literature data to determine variations for different alternative powertrain types. The reference powertrains for different vehicle types are summarised below:

Vehicle type	Passenger car	LCV/Van	Rigid lorry	Articulated lorry (tractor + trailer)	Urban bus	Coach
Reference powertrain(s)	Petrol ICEV Diesel ICEV	Diesel ICEV	Diesel ICEV	Diesel ICEV	Diesel ICEV	Diesel ICEV

Market average or literature sourced datasets were used to define the reference vehicle/powertrains and key specification including total vehicle mass, engine power, as well as the mass of key components for the reference vehicles. This information, together with range assumptions for powertrains operating on alternative fuels or electricity, has been used in conjunction with scaling factors or similar methods to determine the characteristics of individual components for different generic/broadly equivalent vehicle, segment and powertrain types. The developed assumptions for this methodology underwent internal review with Ricardo's engineering experts, and a subset of the most important assumptions were also reviewed in an external data validation exercise with expert stakeholders (discussed in Appendix A2). A summary of the methodologies used to determine the key vehicle or component parameters is provided in Table A20 below, with a matrix of the components applicable to different powertrain types also provided in Table A21. Further information on the specific sources and examples of key foreground datasets are provided in Appendix Section A4.3.

Table A20: Overview of methodologies for determination of vehicle / component specifications

Component	Determination	Scaling parameter	Variation in determination by vehicle type
Total mass	Market data for reference vehicle; Mass for other powertrains is calculated based on mass for the Glider + powertrain components (i.e. including also calculated battery capacity/mass)	N/A	Reference: all types and segments Other powertrains: only via scaling parameters / method
Glider mass	Subtract individual powertrain component masses from the reference vehicle powertrain	N/A	All types and segments
Trailer system	Market data/ literature	Fixed mass	Articulated lorries only
Engine	Market data/ scaling factor	% kW engine reference	Vary reference powertrain by vehicle type and segment. Vary scaling factor for LDV, HDV
Transmission	Market data/ literature	Fixed mass	All types and segments, powertrain
Exhaust system	Scaling factor	Litres engine capacity	Vary scaling factor for LDV, HDV
Aftertreatment	Scaling factor	Litres engine capacity	Vary scaling factor for LDV and HDV, SI, SI (Natural Gas) and CI engines
Fuel tank	Market data/ literature	Fixed mass	All types
Gaseous fuel storage	Scaling factor	Range (km) and MJ/km	Only via scaling parameters / method
Motor	Scaling factor based on market data	% of kW engine	Only via scaling parameters / method
Battery (traction)	Calculated kWh capacity, and battery energy (kWh) density (Wh/kg) assumptions (5)	Range (km) and MJ/km	Determined only via scaling parameters / method (i.e. including required electric km range under test-conditions)
On-board charger	Market data / literature	Fixed mass	All types
Power electronics (3)	Market data / literature	Fixed mass	All types
Pantograph for dynamic charging	Market data / literature	Fixed mass	Articulated lorries only
Fuel cell system (4)	Scaling factor based on market data/ literature	% of kW motor	By vehicle type, powertrain (i.e. different for FCEV, FC-REEV)
H_2 storage	KgH_2 capacity, storage system density (kgH_2/kg)	Range (km) and MJ/km	Only via scaling parameters / method

Notes: (1) Transmission requirements vary depending on the specific configuration, (2) also needed for dual-/bi-fuel vehicles, (3) Inverter, Boost converter, Power control unit, Wiring harness, Regenerative braking system, HVAC heat-pump; (4) Fuel cell stack, Fuel cell peripherals. (5) See later subsection A3.13.1.3 for further information; default results were also cross-checked/compared with current market models as a sense-check.

Table A21: An overview of the modular approach applied to vehicle production configurations

Component	ICEV Liquid	ICEV Gaseous	HEV	HEV -ERS	PHEV or REEV	BEV	BEV -ERS	FCEV	FCEV -REEV
Glider	Y	Y	Y	Y	Y	Y	Y	Y	Y
Trailer system (artic lorries only)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Engine (ICE)	Y	Y	Y	Y	Y				
Transmission (1)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Exhaust system	Y	Y	Y	Y	Y				
Aftertreatment (2)	Y	Y	Y	Y	Y				
Fuel tank	Y	(3)	Y	Y	Y				
Gaseous fuel storage (4)		Y						Y	Y
Motor			Y	Y	Y	Y	Y	Y	Y
Battery (traction)			Y	Y	Y	Y	Y	Y	Y
On-board charger					Y	Y	Y		Y
Power electronics (5)			Y	Y	Y	Y	Y	Y	Y
Pantograph for dynamic charging system				Y			Y		
Fuel cell system (6)								Y	Y

Notes: (1) Transmission requirements vary depending on the specific configuration and type (e.g. single gear-ratio common for BEVs); (2) Different for petrol, diesel and for gas vehicles; (3) also needed for dual-/bi-fuel vehicles; (4) Different types - e.g. CNG, LNG, LPG, hydrogen; (5) Inverter, Boost converter, Power control unit, Wiring harness, Regenerative braking system, HVAC heat-pump (6) Fuel cell stack, Fuel cell peripherals.

A3.13.1.1.1 Definition of assumptions for light duty vehicles (cars and vans):

Average parameters (vehicle mass, engine power, regulatory energy consumption per km, etc.) for car and van reference powertrains were developed based upon an updated analysis of the most recent car and van CO_2 monitoring databases, using a similar methodology as that employed in previous analysis for DG CLIMA (Ricardo Energy & Environment et al, 2016) and (Ricardo Energy & Environment et al., 2018), as also discussed in the main report, Section 3.5.

The baseline component specifications and scaling factors / other assumptions for different powertrain components were based upon previous analysis (e.g. in the above sources, wider literature), updated based on consultation with Ricardo's vehicle engineering subject experts.

The forward projections for improvements to new vehicle energy consumption for the baseline vehicles and alternative powertrain options was based upon PRIMES-TREMOVE modelling scenario datasets provided by DG CLIMA for two scenarios.

A limited stakeholder exercise was also conducted to validate / check particularly key assumptions such as the electric range assumptions for 'average' future vehicles with xEV powertrains (see Appendix A2).

A3.13.1.1.2 Definition of assumptions for heavy duty vehicles (lorries and buses):

Average parameters (vehicle mass, component masses, engine power, etc.) for different heavy-duty vehicle types (i.e. lorries, buses and coaches) was based upon a combination of baseline data from previous Commission analysis projects (e.g. (Ricardo Energy & Environment et al., 2015), (TNO et al., 2018)) and VECTO simulation model default values.

HDV-specific scaling factors / other assumptions for different powertrain components were developed based on a consultation with Ricardo's vehicle engineering subject experts.

As for LDVs, the forward projections for improvements to new vehicle energy consumption for the baseline vehicles and alternative powertrain options was based upon PRIMES-TREMOVE modelling scenario datasets provided by DG CLIMA.

Also as for LDVs, a limited stakeholder exercise was conducted to validate particularly key assumptions such as the electric range assumptions and battery sizing for 'average' future vehicles with xEV powertrains (which are particularly uncertain as models are only starting to be introduced to the market).

A3.13.1.2 Vehicle unladen mass and composition

The characterisation of vehicle's mass and composition was based upon the reference ICEV vehicle type and its sub-division into its different components/systems. These components were scaled /substituted with those relevant for alternative powertrain configurations (i.e. as defined in Table A21) to determine the final vehicle mass. The corresponding material composition for a given powertrain type was based on generic compositions for specific components (sourced mainly from the GREET 2 model and other sources – see below), scaled to the specific vehicle type and powertrain parameters/mass. The process is illustrated in the following Figure A49, following the following steps:

1. Define EU average mass and material composition for baseline ICEV reference vehicle body types based on pre-existing sources/analyses, normalised to current market averages.
2. Define variations for different powertrain types based on defined sizing /composition of key components (i.e. glider, ICE, transmission, electric motor, battery, etc) – i.e. as in Table A20.
3. Utilise fixed projections with assumptions for future changes in mass and material composition by vehicle type for the glider, and for other key components (across all vehicle types) – with particular detail for batteries and fuel cells (see Section A3.13.1.3 for further information).

This approach allowed for customisation of different vehicle sizes and component specifications (e.g. also different sized batteries), as well a transparent and systematic way to account for future changes / improvements to the mass and composition of the individual components and the overall vehicle.

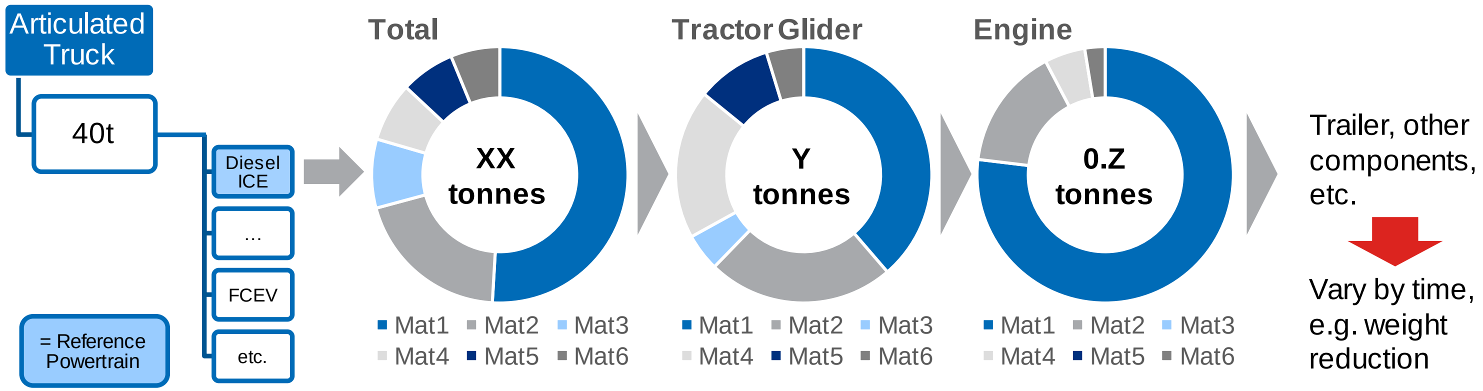
A3.13.1.2.1 Key sources of assumptions for vehicle and component data:

The assumptions for vehicle unladen mass and composition were developed based upon a combination of Ricardo's recent relevant work in this area, such as (Ricardo, 2017) for light-duty vehicles and (Ricardo Energy & Environment et al., 2015) for heavy duty vehicles, together with other sources such as the GREET 2 model (ANL, 2018) and inventories developed for various xEV powertrain components by Chalmers University (e.g. (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014)).

The core datasets were also supplemented with material from other sources, and gap-filling with Ricardo's internal experts and key stakeholders where gaps or uncertainties existed.

Figure A49: Illustration of the component-based methodology developed for defining vehicle composition and mass for alternative powertrains

- Define reference vehicle / default powertrain by body type – e.g. Diesel Artic 40 t GVW
  - Example: convert Diesel ICEV to FCEV or BEV:
    - Replace engine with motor: ***X*** kW ICE * ***y***% (scaling factor) = ***Z*** kW electric motor
    - Mass motor (kg) = Z * motor power density (kg/kW)
    - Similarly for changing/sizing other components (with generic parameters and compositions)
- **Illustration** for composition and mass for reference vehicle:



Notes: Ma1, Mat2, etc. = Material 1, Material 2, etc.

A3.13.1.3 Energy storage and fuel cells

The size / specification of energy storage and fuel cells is a key assumption that has a significant impact on the assessment of xEV powertrains, and is linked to other vehicle specification and performance parameters. The developed methodology uses a range of the following key vehicle parameters to define the size of the energy storage and fuel cell systems, including:

Energy consumption in MJ/km	Average energy consumption of the vehicle when operating on a specific fuel or electricity (defined under the relevant regulatory cycle), see also A3.13.3.
Required operational range	The required operational range (on the relevant regulatory duty cycle – which is assumed to be targeted in vehicle development) on a given fuel or electricity. This parameter is varied by vehicle type and segment, and the expectations for operational range are also assumed to vary over time (e.g. as battery performance improves and costs reduce, longer average ranges are anticipated for BEVs).
Reserved state of charge (SoC) for batteries	The initially reserved state of charge for an average battery for a given vehicle powertrain type (varies for hybrid, plug-in hybrid and fully electric vehicles)
Peak motor power (kW)	Vehicle peak power requirement is used primarily for sizing of fuel cell systems for vehicles using these, though an additional sizing parameter may also be included for certain vehicle/powertrain variants.
Fuel cell sizing % of max motor power	As indicated above, a smaller fuel cell may be used for range-extended fuel cell electric vehicles at least.

There are also further considerations relating to the specific composition and mass of the energy storage system and fuel cells (i.e. related to energy density – Wh/kg, or power density – W/kg), which are further discussed below.

The end-of-life accounting applied in the project methodology also considers the implications of second-life batteries, which has also been explored as a sensitivity (see also Section A3.13.4).

For xEV traction battery storage:

$$\mathbf{C}\,[Battery\ total] = \frac{(\mathbf{E}\,[Average] \times \mathbf{R})}{(1 - \mathbf{SoC}\%)}$$

Where

C [Battery total] = total traction battery capacity in kWh

C [Battery usable] = usable traction battery capacity in kWh = **E** [Average] × **R**

SoC% = average battery initially reserved state of charge for a given vehicle powertrain type, in %

R = targeted vehicle range operating on fuel or electricity (in km)

E [Average] = vehicle average energy (fuel or electricity) consumption, in MJ or kWh per km

The methodology employed to establish the number of battery replacements that is required over the life of the vehicle is summarised in later Section A3.13.3.4.

For gaseous energy storage:

$$\mathbf{CF} = \mathbf{E}\,[\mathrm{Average}] \times \mathbf{R}$$

Where

CF = total gaseous fuel storage capacity in kg (or litres) of fuel.

For the hydrogen fuel cell system:

$$\mathbf{P}\,[fuel\ cell] = \mathbf{P}\,[motor] \times \mathbf{FCS}$$

Where

P [fuel cell] = fuel cell power in kW

P [motor] = peak motor power for the vehicle in kW

FCS = vehicle and powertrain-specific fuel cell sizing parameter in % of peak motor power (kW)

A3.13.1.3.1 Key data sources and assumptions

The underlying datasets were mainly built upon and expanded from Ricardo's previous work for the European Commission on light-duty and heavy-duty vehicles, also using datasets from GREET 2 (ANL, 2018) and other literature sources to define (Li-ion) batteries, fuel cell systems and gaseous storage, etc. Key assumptions used to define energy storage sizing where validated with stakeholder experts also as part of the limited validation exercise (see Appendix A2).

To account for changes in technology, future projections for improvements in battery energy density and composition were developed (i.e. as far as possible to account for shifts from current lithium ion to new chemistries, such as using solid-state electrolytes or sodium-ion chemistries).

Further information is provided on the specific assumptions in the main report, and also in later Appendix Section A4.3.2.1.

A3.13.2 Vehicle manufacturing

The modelling of vehicle manufacturing (beyond the impacts from material production chains) was based on information on the materials required to build the vehicle (material demand) and the necessary manufacturing/assembly process energy (Figure A50 and Table A22). Thus the following elements are involved in the calculations:

- Material production chains based on the LCI background data (see Section A3.10)
- Material demand for vehicle production/assembly (including auxiliary materials)
- Energy demand for vehicle production/assembly

For these elements, further considerations were necessary relating to spatial aspects (i.e. where does the manufacturing process take place) and temporal development (what will this process demand in the future). These considerations and practical implementation are described in the following sections. The focus is on a consistent and sound approach to assess differing components between vehicle types (especially batteries).

Figure A50: Schematic illustration of approach towards vehicle production

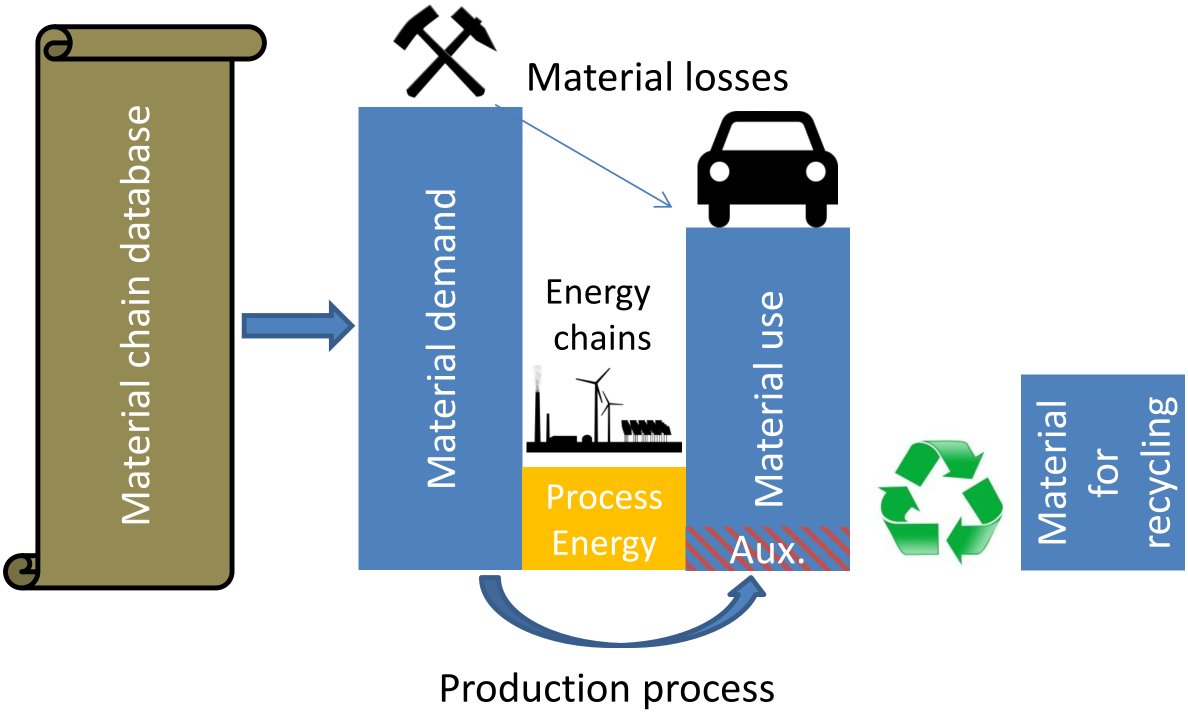


Table A22: Summary of the approach for accounting for temporal developments in vehicle production

Data type	Modelling of current situation	Temporal development
Material chains	The background database as discussed in A3.10 is used.	Future changes in material production impacts are based on projections for changes in electricity generation mix/decarbonisation.
Material demand	Differentiated material compositions, material losses and auxiliary materials are considered for generic vehicles in a modular/component-based way. General market datasets are used.	Changes with vehicle specification, share of light-weight material and development of batteries (variation in future mix of chemistries and energy density in Wh/kg) are considered.
Process energy	For electricity used in vehicle production a representative electricity mix reflecting the market mix of EU new registrations by country of production (based on ACEA EU vehicle production statistics and Eurostat data on imports). For batteries, the countries of origin for the battery cathode, battery cell and battery pack assembly stages are considered separately and used to derive appropriate electricity mixes.	Decarbonisation of process energy, largely following the relevant scenario for the defined mix of EU (and intra-EU for vehicle manufacturing/assembly) and non-EU regional manufacturing (covering China, S. Korea, Japan, USA and (rest of the) World).

A3.13.2.1 Material chains

Current situation

The defined **material production chains** are based on the background database (see Section A3.10), which is mostly based on ecoinvent 3. In ecoinvent 3, market mixes are used to calculate consumption mixes of a certain product in a certain geographical region (either local markets or global, depending on the products are considered).

Temporal development

A temporal development is usually not included in existing background LCI - most commonly accepted databases refer only to the current situation. Nevertheless, the study incorporates temporal aspects with a focus on decarbonisation of electricity used for producing the materials, as discussed in earlier Section A3.10.1.

A3.13.2.2 Material demand

Material chains only state the impact associated with the provision of material, but do not include information on the amount of material required. For different components therefore the individual material demand is defined, including material losses and auxiliary materials used in the production process. The modular approach adopted in this study allows for a differentiated spatial/temporal variability since production sites tend to differ by vehicle component (especially for battery cells which are currently mostly produced outside the EU) and are characterised by different energy mixes. This also enhances transparency as many materials are used in several components. Auxiliary materials are also needed for the production process but are mostly of minor importance.

Current situation

Material demand for vehicle production is modelled based on the technical vehicle specifications (see Section A3.13.1), plus additional material processing and/or material loss factors (see Appendix Sections A4.1 and A4.3.2). The modular approach developed uses different gliders defined by vehicle type (see Section A3.4.1) and adds powertrain specific components scaled according to the vehicle specifications (see Section A3.13.1). This approach also allows for the transfer of material compositions to vehicle types (and powertrains) that have not been covered significantly in the identified LCA literature previously (e.g. coaches), but where more general information on their specification and characteristics is available from other work.

The material composition of the **glider** (i.e. excluding powertrain, energy storage, components, etc.) has been standardised for each of the six generic body types (i.e. car, van, rigid lorry, articulated lorry, bus, coach), plus also some adjustments made to account for differences between lower medium cars and large SUVs. Reasonable care has been taken to reflect the average market mix for vehicle bodies, and the baseline reference powertrain assumptions for these were reviewed/validated with both internal Ricardo engineering experts, and with external stakeholder experts in a data validation exercise (see Appendix A2). This approach was chosen to ensure practical feasibility within the project, even though the diverse vehicle market in reality may lead to significant differences in the material composition for specific vehicle types. (A sensitivity on this aspect was also performed, summarised in the main report).

The different powertrain-specific components are calculated similarly between different vehicle types using appropriate scaling factors based on the vehicle specifications (e.g. weight, engine power, battery capacity). The considered components are listed and allocated to the different powertrains in Table A21. The general material composition of the components is applied to all vehicle types, except for the 'Glider', which is specific to a particular vehicle type.

Temporal development

The following temporal developments for material demand were considered in the LCI modelling:

- The temporal development of key vehicle specifications leads to a shift in overall material demand by different component sizes. In particular, the use of lightweight materials in the glider (and corresponding assumptions on glider mass reduction) and changes to battery chemistry over time are modelled. The overall vehicle size/definition itself is not varied over time, though reduction in the total mass of the glider is assumed in the calculations and is linked to the material composition in the glider.
- Changes in the material composition of the vehicle glider will not affect results in a comparative assessment between different powertrain and fuel types. Therefore only a change in the share of light-weight material (e.g. aluminium) is accounted for (linked also to a change in the mass).
- Further changes in material composition was restricted to batteries. Here the development of future cell chemistries (e.g. 8-1-1 NMC) was considered, and is discussed later. Development of the battery energy density (in Wh/kg battery) also has an impact on the total amount of battery materials used.

7.1.1.1 Process energy

Current situation

Process energy is often of relevance and consists mostly of electricity, but potentially also other energy carriers. The total general manufacturing/assembly energy consumption assumptions are based on defaults from the GREET model (ANL, 2018); separate accounting is provided for the manufacturing of xEV batteries. Electricity generation relies on the modelling approach developed in this project, with an adjustment to convert the impacts based on low voltage network output (from the main calculations) to impacts based on consumption at medium voltage (i.e. as typical for large industrial facilities). Further information on these conversions is provided in Appendix A4.

As well as European vehicle producing countries, countries producing imported vehicles also need to be considered. Therefore the methodology calculates impacts based on a weighted average electricity generation mix reflecting the national generation mixes in the market mix of EU new registrations by country (based on ACEA/OICA vehicle production statistics and Eurostat data on imports).

In a similar way, the countries of origin are considered for the battery to reflect (separately) the current regional manufacturing shares for the cathode materials, cell manufacturing and battery pack assembly. Currently batteries are largely produced in East Asia and the US for which the carbon intensity is much higher than the EU average.

Further information on the specific foreground data assumptions implemented in the calculations for vehicle and battery manufacturing is also provided in Appendix A4.

Box 10: Additional commentary on the developed approach

> The proposal to factor in the location of <u>vehicle</u> production into the analysis was broadly supported by stakeholders in Round 2 of the Delphi Survey, also confirming the analysis to consider the EU mix as well as other key regions including primarily China, Japan, the USA and South Korea.

Future situation

Process energy for vehicle manufacturing/assembly is likely to decarbonise as is expected for material chains. In addition to decarbonisation in the countries which supply certain materials or parts of a vehicle (e.g. the battery cell), changes in the countries of origin for key components or materials may occur. This is especially relevant for battery cell manufacturing where cell manufacturing capacity worldwide is fast increasing, and European production capacity is under rapid expansion at the moment, with a number of factories are being planned in Europe. To explore uncertainty in how this will develop after 2020, alternative scenarios for future increases in the EU share of battery production have been developed: one with a more global cell production (and a lower rate of growth in the share of EU production) and one with a high share of cells produced in the EU (reaching levels similar to those of the overall vehicle manufacturing share by 2050).

A3.13.2.3 LCI data sources

Original, well documented LCI data for vehicle manufacturing is still rare. Looking at the range of literature sources examined, it can be concluded that lots of studies refer to just a few original sources for LCI data.

A range of powertrains were covered in the reviewed literature, and while conventional vehicles as well as established alternative powertrains like electric mobility were well covered, plug-in hybrids and fuel cell vehicles received far less attention. In terms of vehicle types, passenger cars attract significantly greater attention than other vehicles. The developed methodological approach of scaling of components to other vehicle applications is therefore of importance to broaden the database.

Table A23 shows the main sources of battery LCI data found in literature.

Table A23: LCI data sources for lithium-ion batteries (according to (Peters J. B., 2017))

LCI data source	Year	Source type	Disclosure
Hischier et al.	2007	LCI database (included in ecoinvent)	Documentation in the form of reports
Zackrisson et al.	2010	own / original LCI data	Proper documentation within the scientific article
Notter et al.	2010	own / original LCI data	Bill of materials, description of unit processes
Majeau-Bettez et al.	2011	own / original LCI data	Comprehensive report on modelling including detailed description of the processes
Dunn et al.	2014	LCI database (included in the GREET model)	Comprehensive report on modelling including detailed description of the processes
US-EPA	2013	own / original LCI data	Comprehensive report on material and process data, discussion of uncertainty in the data
Ellingsen et al.	2014	own / original LCI data	Comprehensive supplemental information
Troy et al.	2016	own / original LCI data	Brief description of data

Due to the high level of quality, comprehensive detail and transparency provided, the battery cell/pack characterisation methodology, and data for battery manufacturing and recycling calculations, is mainly based upon that provided in the Argonne National Laboratory GREET model (ANL, 2018) and EverBatt battery recycling model (ANL, 2018a) for Li-ion batteries. However, the specific impact factors for materials used in battery manufacturing and recycling are taken from the developed LCI background dataset developed for this project. Additional modification/expansion has been based on other sources to enhance detail in particular areas, and to estimate the impacts of potential new battery chemistries not already covered in GREET. This has built upon Ricardo's recent work for EC JRC (Ricardo Energy & Environment, 2019). An 'average' xEV battery is modelled in the LCA based on chemistry-specific battery characterisations and a future projection for the change in market percentage share for these, and in improvements to battery energy density (see also earlier discussion in Section A3.13.1.3). The LCA calculation framework for the project was also set up to allow for sensitivities on the key assumptions on market share and energy density improvement in the LCA application.

Further details on these specific foreground data assumptions has also been provided in the main report, and further information is also provided in later Appendix A4.

A3.13.3 Vehicle operation and maintenance

The characterisation of impacts from vehicle operation are dependent primarily on the following four parameters, summarised in Table A24. The methodology for defining these key elements is summarised in the following subsections.

A3.13.3.1 Vehicle operational energy consumption

Vehicle operational energy consumption accounts for the largest share of impacts for most vehicle / powertrain / fuel combinations, so it is appropriate to characterise this in more detail than other areas.

The methodology developed accounts for the most important aspects of variability in the operational energy consumption, allowing also for suitable sensitivities to be carried out on key assumptions.

An illustration of the developed methodological process to calculated relevant foreground data assumptions is provided in Figure A51. A summary of the key steps provided also below, followed by a worked example of the methodology for a Lower Medium Car Gasoline PHEV powertrain in Table A26.

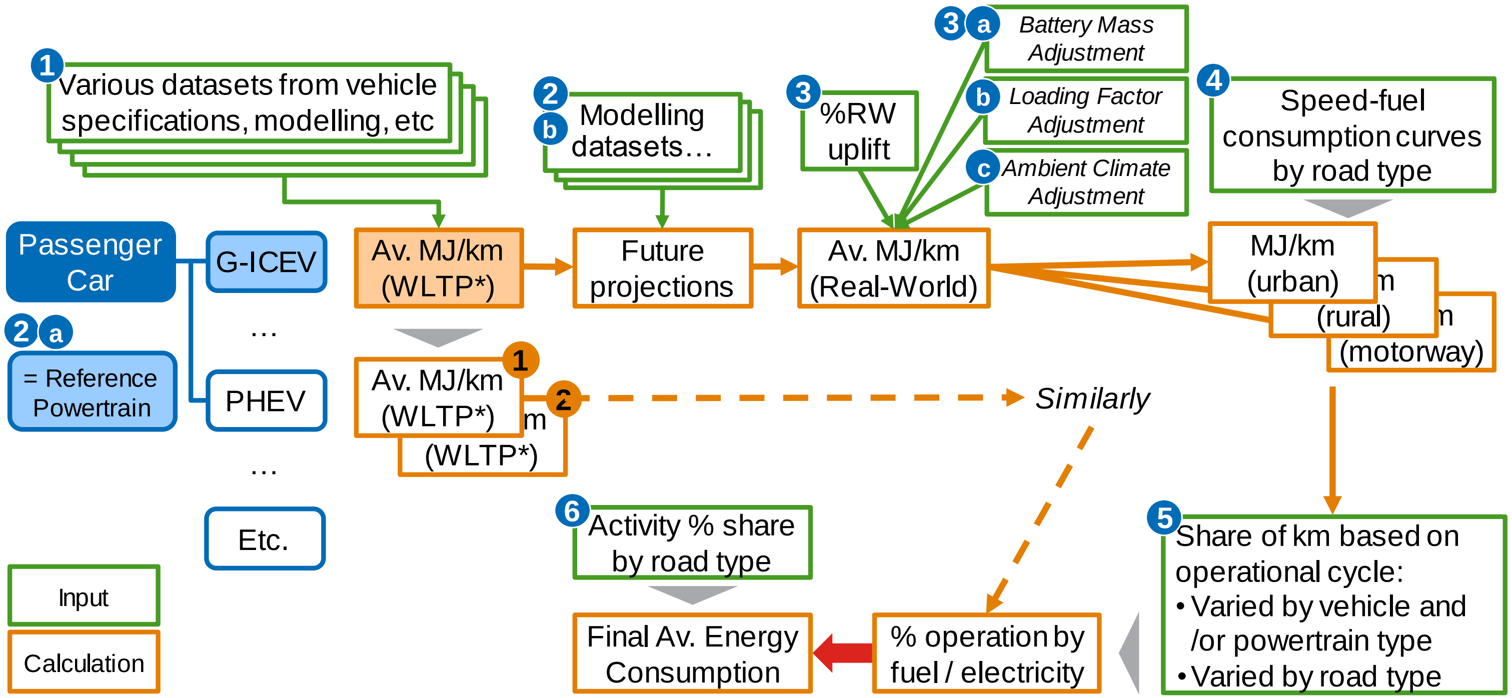
Table A24: Key parameters for vehicle operational use impacts

Data / parameter type	Summary description
Energy consumption (Section A3.13.3.1)	The operational (use) energy consumption depends upon the technical efficiency of the vehicle and the (regulatory/) operational duty cycle, which can be influenced by a wide range of parameters in the real-world (such as loaded mass, climatic conditions, road conditions, speed, etc). For vehicles able to operate on more than one fuel (e.g. dual-fuel gas-diesel vehicles or plug-in hybrid electric vehicles) it is necessary to also specify the share of operation on the different fuel/energy types.
Vehicle direct emissions (Section A3.13.3.2)	This includes (i) tailpipe emissions based directly on the consumption of relevant fuels (e.g. CO_2, SO_2), as well as (ii) tailpipe and non-tailpipe emissions that are not (e.g. other regulated air quality pollutants, PM emissions from tyre/brake wear, etc.).
Activity and lifetime (Section A3.13.3.3)	The importance of the operational phase is strongly influenced by the annual mileage profile (i.e. newer vehicles tend to have significantly higher annual mileage) and the overall lifetime of the vehicle (in years).
Vehicle maintenance and component replacement (A3.13.3.4)	Including servicing and replacement parts over the vehicle lifetime (i.e. including routine replacements, such as tyres and oil, as well as items replaced due to fault/damage – e.g. exhausts, batteries, etc.).

Steps 1, 2a. Defining the energy consumption performance on regulatory cycles for different vehicle and powertrain types

The first two steps in the development of the foreground dataset were to characterise the average energy consumption performance of the reference powertrains for the different vehicle types (and any segments below these) in the base year, and then to calculate equivalent figures for the alternative powertrains relative to these, using input assumptions on the % energy consumption of the alternative powertrains relative the reference powertrain (see Appendix Section A4.3). This produces energy consumption (in MJ/km) for vehicles operating on different fuel types according to regulatory cycles. The regulatory-based datasets were taken to be on a default WLTP-basis for light-duty vehicles, and based on the relevant VECTO duty cycle for heavy-duty vehicles, as illustrated in Table A25 below.

Figure A51: Illustration of the methodological steps implemented for defining the energy consumption for different vehicle types and powertrains



* WLTP for LDVs, alternative regulatory cycles for HDVs (i.e. as defined for whole-vehicle fuel consumption/CO_2 certification using VECTO)

Table A25: Summary of the regulatory cycles covered in the vehicle LCA modelling

Input/Output	Cycle	Cars	Vans	12t Rigid Lorry	40t Artic Lorry	12m SD Bus	24t SD Coach
Input, Sensitivity Output	Cycle1 (default)	WLTP	WLTP	Urban Delivery*	Long Haul*	City-bus urban*	Coach*
Sensitivity Output	Cycle2 (alternative)	NEDC	NEDC	Regional Delivery*	Regional Delivery*	N/A	N/A
Default/Main Output	Real-World (RW)	See Figure A51	See Figure A51	See Figure A51	See Figure A51	See Figure A51	See Figure A51

Notes: * Duty cycles as defined in the VECTO model used for EU HDV fuel consumption and CO_2 certification. The default output from the model are the 'Real-World' cycle results, calculated according to the defined methodology.

Box 11: Additional commentary on the approach for vehicle operational energy consumption

The majority of the vehicle manufacturers consulted during the project indicated a preference for only using regulatory-based energy consumption (and tailpipe emissions) data in the LCA. However, this is not consistent with the goal of the study which is to inform policy understanding on real-world impacts.

Step 2b: Future projected changes in energy consumption

Future improvements (up to 2050) in vehicle/powertrain energy consumption performance, in part driven by regulatory requirements, need to be accounted for in the analysis. To achieve this, the applied methodology utilised specific European Commission scenario modelling datasets, developed to meet future policy objectives (as outlined in the main report, Section 4.7.1). Two scenarios were utilised, a baseline scenario and a scenario compatible with meeting the Paris Agreement objectives, as summarised in the main body of the report. These datasets were used to define the relative improvement of individual vehicle and powertrain types relative to the 2020 vehicle baselines developed within this project, i.e. using the calculation below:

20XX Vehicle MJ/km = 2020 Baseline Vehicle MJ/km x % change 2020-20XX from EC modelling

Step 3. Converting test-cycle (TC) data to real-world (RW) basis

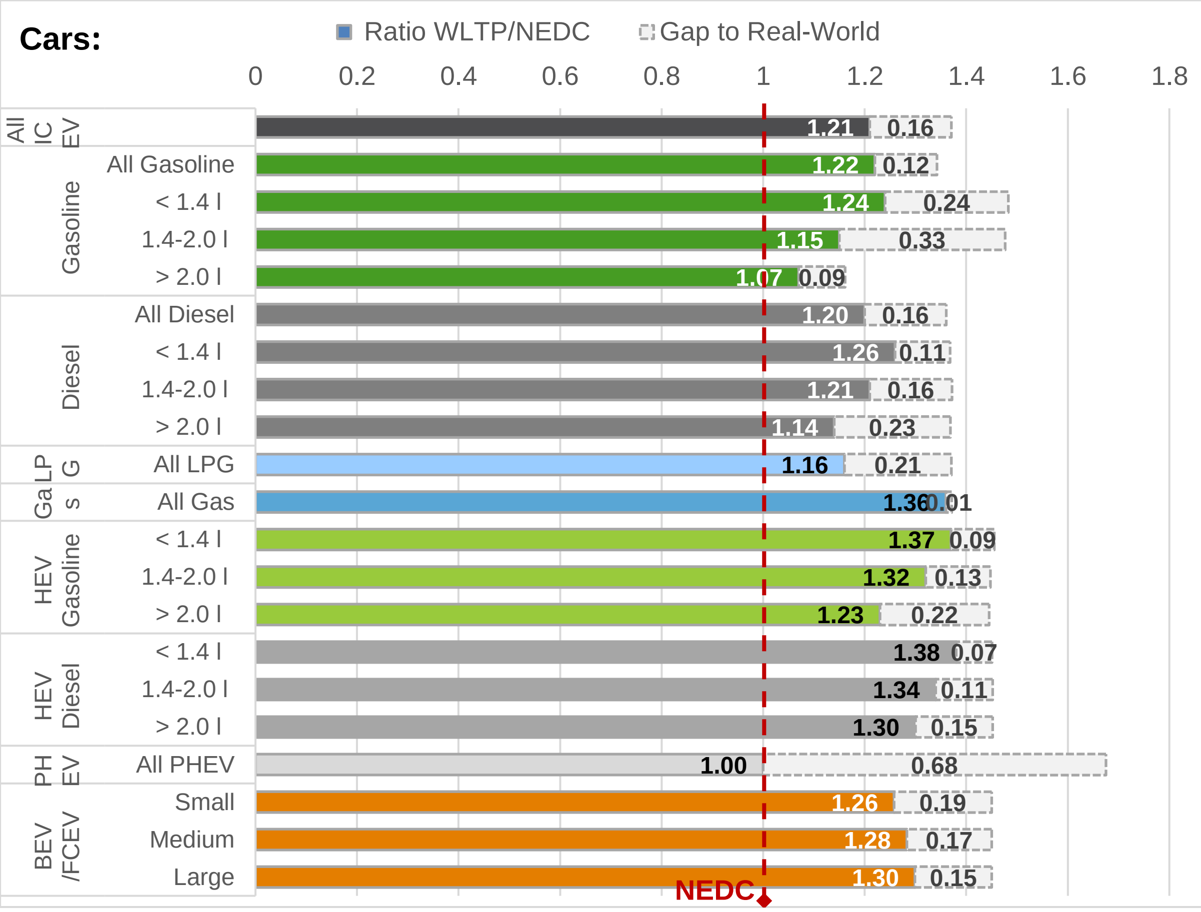
For LDVs only, NEDC-based CO_2 monitoring derived MJ/km datasets were converted outside of the model to WLTP equivalents for the vehicle reference powertrain as inputs to earlier Step1. Inside the model, the further conversion from WLTP to Real-World equivalents was carried out in Step 3. Both used data from analysis by JRC (illustrated in Figure A52 below) using the relevant correlation factor for the specific vehicle category and fuel/powertrain type. Further information on the specific assumptions used for all vehicle types is provided in later Appendix A4. These preliminary 'Real-World' performance equivalents are be taken to represent the average EU position based on central assumptions for battery size/energy density, vehicle loading (e.g. with freight) and for the average climatic conditions in the EU. For HDVs it is assumed that performance based on VECTO outputs (e.g. from (JRC, 2018)) is a good representation of baseline real-world performance over these cycles (in the absence of an equivalent dataset), and so only a correction for the difference between the road shares for the default test cycle, and those for average EU28 conditions is applied.

A number of sensitivity parameters were also included (as steps 3a, 3b and 3c), to allow for adjustments in real-world energy consumption due to variations in the assumptions for total vehicle mass via battery size/mass, freight loading, and ambient climate variation/temperature. These adjustments were made based on simple scaling factors relating to the relevant vehicle type, powertrain (and potentially also duty cycle assumed) using established physical relationships, and are summarised in the next sections.

Box 12: Additional commentary on the approach for converting test-cycle data to real-world basis

The additional adjustments for (a) battery mass, (b) vehicle loading, (c) ambient climate conditions were included for investigation based on feedback from the Delphi survey and stakeholder workshop. However, their final implementation in the methodology / application was based upon the respective feasibility/complexity and the availability of suitable data – in particular for ambient climate effects, where suitable data was only available for LDVs.

Figure A52: Estimates for the ratio of NEDC-based CO_2 emissions/energy consumption to WLTP and Real-World



Source: (JRC, 2017a), (Ricardo Energy & Environment et al., 2018)

Step 3a: Adjustment for battery storage mass

Where the settings impacting battery mass are adjusted away from their defaults for the purposes of exploring sensitivities (i.e. electric range and battery energy density) the difference in the calculated mass of the battery used in the vehicle (versus default) is used to calculate an adjustment to the average energy consumption (in MJ/km) of the vehicle based on a standardised average relationship for the % change in energy consumption per % change in mass (specific to the vehicle and powertrain type).

These mass:energy relationships were defined for LDVs in previous simulation analysis for DG CLIMA (Ricardo Energy & Environment et al, 2016), and for HDVs by Ricardo's own simulation analysis for using the standard VECTO regulatory cycles for different vehicle and powertrain types.

Step 3b: Adjustment for vehicle load factor

For heavy-duty vehicles only, where the settings for vehicle load factors are switched away from the average loading default setting (i.e. to explore sensitivities on this) the difference in total laden vehicle mass is calculated. Similarly as for the battery storage mass adjustments, the mass:energy consumption relationships are used to calculate the impact on total energy consumption from this. Load-specific emission factors are also applied for air quality pollutant emissions, based on the same COPERT speed-emission curve formulae (which also include formulae for operation full, 50% loading and empty).

Step 3c: Adjustment for ambient temperature

The applied calculation model also allows for sensitivities on the variation in average ambient temperature to be applied through simple % adjustments to the total energy consumption (by vehicle and powertrain type) depending on the average temperature setting (and its variation from the defined EU-average setting upon which the default real-world energy consumption is based). No suitable datasets on the ambient temperature effects on vehicle energy consumption were identified/available for heavy-duty vehicles, however these could be added in the future should such data become available.

This adjustment also allows for a limited accounting for regional variation in real-world energy consumption to be calculated (based on annual average ambient temperature) in conjunction with the other regional effects (i.e. also mileage share by road type – see below, and regional electricity mix).

Steps 4, 5: Accounting for the share and variation in energy consumption by road type

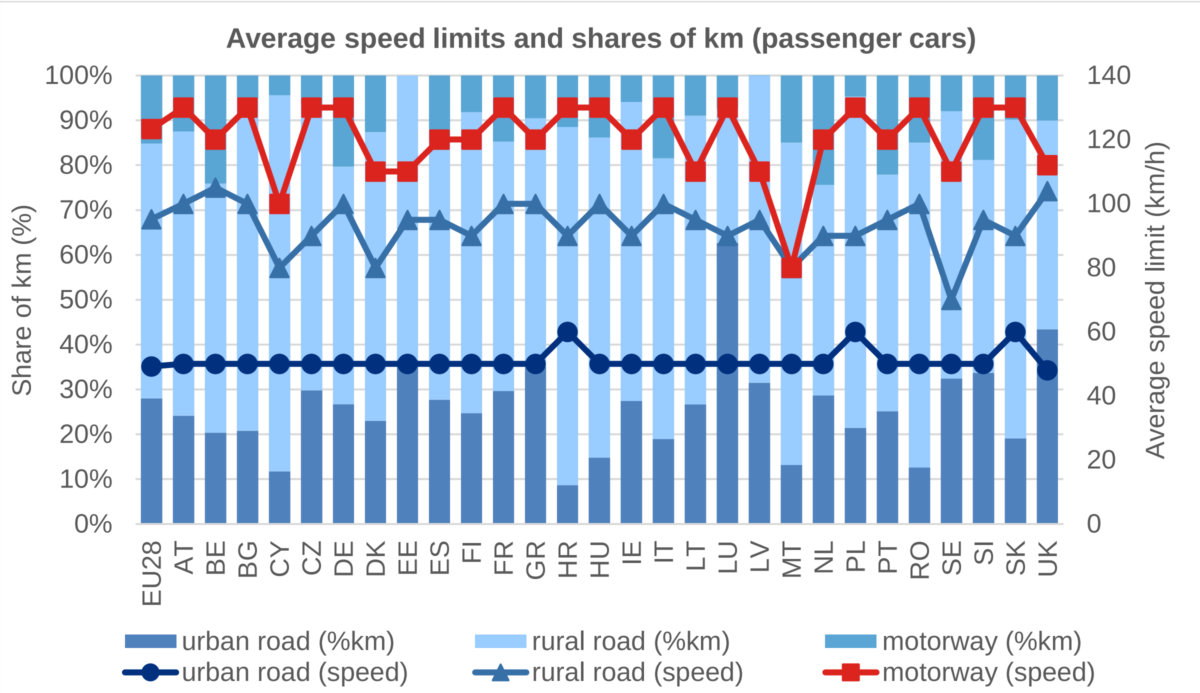
Real-world energy consumption (and also direct emissions of air quality pollutants) is strongly affected by driving conditions, particularly average speed and the transience in this. The relationship with average speed also varies by powertrain type.

In Step 4, the average energy consumption for different powertrains / fuel types is calculated for different road types. These mainly use pre-existing inventory speed-energy consumption formulae (from COPERT, (Emisia, 2019)) and datasets on the average speeds and km shares of vehicle-km on different road types (the latter from EC modelling data provided by DG CLIMA). For variation in energy consumption from heavy-duty vehicles, datasets based on Ricardo simulation analysis carried out for this project have been used instead to also estimate variations due to newer HDV powertrains that are not covered by COPERT/other inventory sources. These results are used to scale the average real-world energy consumption data, derived in the previous step, for specific road types.

In Step 5, these road-specific energy consumption factors are used in combination with data on the different operational shares by road type for different vehicles or regions/countries to calculate the total energy consumption for the selected region/cycle.

This methodology allows for the exploration of sensitivities in overall energy consumption to reflect variation in countries across the EU, and to also help quantify emissions of air pollutants that have variable impacts based on location of emission (discussed also in Section A3.13.3.2). Figure A56 provides an illustration of the variability in average speed and activity across the EU for passenger cars.

Figure A53: Summary of the variability in average speed limits and activity by mode across the EU for LDVs



Source: Analysis of PRIME-TREMOVE modelling scenario datasets provided by the EC for this study, transport statistics and the TREMOVE model (AEA et al., 2012).

Step 6: Fuel operation split for dual-fuel / PHEVs

For powertrain options using more than one type of energy carrier – e.g. dual-fuel vehicles or plug-in hybrid vehicles – separate accounting is applied for the average share of operation of the vehicle on these different fuel types (and also a variable share on different road types, where priority can be set to urban driving as a sensitivity). For PHEVs, this share is based on the separate Utility Factor assumptions for LDVs and for HDVs and is based upon the calculated (regulatory or real-world) operation/duty cycle being explored. The applied calculation framework also allows for sensitivities to be considered to reflect concerns over extreme cases (e.g. owners not regularly plugging in PHEVs, or in contrast making more significant efforts to operate in electric mode).

Table A26: Illustration of the step-by-step calculation of real-world energy consumption for a Lower Medium Car Gasoline PHEV; Sensitivity settings: High Elec Range, Operation in Sweden (SE).

Key: Fuel1 = Gasoline; Fuel2 = Electricity

#	Step	Fuel	Road	Parameter	2020	2030*	Note
1	**Reference powertrain**	Fuel1	All	MJ/km	2.1730	N/A	
2a	***Alt. powertrain energy cons.***	Fuel1	All	%Ref MJ/km	80%	N/A	
		Fuel2	All	%Ref MJ/km	26%	N/A	
2b	***Projected future energy cons.***	Fuel1	All	%2020	100%	95%	
		Fuel2	All	%2020	100%	95%	
	Calculated result (EU)	**Fuel1**	**All**	**MJ/km**	**1.7384**	**1.6517**	
		Fuel2	**All**	**MJ/km**	**0.6205**	**0.5895**	
3	**Real-world uplift**	Fuel1	All	TC-RW factor	1.097	1.097	
		Fuel2	All	TC-RW factor	1.130	1.130	
	Calculated result (EU)	**Fuel1**	**All**	**MJ/km**	**1.9067**	**1.8116**	
		Fuel2	**All**	**MJ/km**	**0.7012**	**0.6662**	
3a	***Battery mass adj.***	All	All	%Mass change*	1.5%	0.7%	(1)
		Fuel1	All	%Energy/Mass	62%	62%	(2)
		Fuel2	All	%Energy/Mass	52%	52%	(2)
	Calculated result (EU)	**Fuel1**	**All**	**MJ/km**	**1.9240**	**1.8194**	
		Fuel2	**All**	**MJ/km**	**0.7066**	**0.6686**	
3b	***Loading factor adj.***	All	All	%Mass change*	0%	0%	(3)
		Fuel1	All	%Energy/Mass	62%	62%	(2)
		Fuel2	All	%Energy/Mass	52%	52%	(2)
	Calculated result (EU)	**Fuel1**	**All**	**MJ/km**	**1.9240**	**1.8194**	
		Fuel2	**All**	**MJ/km**	**0.7066**	**0.6686**	
3c	***Ambient climate adj.***	All	All	ºC change (EU-SE)	-8ºC	-8ºC	(4)
	Calc. from temp. difference	Fuel1	All	%Change MJ/km	106.4%	106.4%	(5)
	Calc. from temp. difference	Fuel2	All	%Change MJ/km	112.0%	112.0%	(5)

#	Step	Fuel	Road	Parameter	2020	2030*	Note
	Calculated result (SE)	**Fuel1**	**All**	**MJ/km**	**2.0472**	**1.9358**	
		Fuel2	**All**	**MJ/km**	**0.7659**	**0.7248**	
4	**Energy cons. by road**	All	Urban	%Share km	32.5%	32.5%	
		All	Rural	%Share km	59.5%	59.5%	
		All	Motorway	%Share km	8.0%	8.0%	
		Fuel1	Urban	%Av. MJ/km	93.5%	93.5%	(6)
		Fuel2	Urban	%Av. MJ/km	77.6%	77.6%	(6)
		Fuel1	Rural	%Av. MJ/km	94.8%	94.8%	(6)
		Fuel2	Rural	%Av. MJ/km	93.3%	93.3%	(6)
		Fuel1	Motorway	%Av. MJ/km	131.2%	131.2%	(6)
		Fuel2	Motorway	%Av. MJ/km	166.5%	166.5%	(6)
	Calculated result (by road)	Fuel1	Urban	MJ/km	1.9150	1.8108	
		Fuel2	Urban	MJ/km	0.5946	0.5627	
		Fuel1	Rural	MJ/km	1.9415	1.8359	
		Fuel2	Rural	MJ/km	0.7143	0.6759	
		Fuel1	Motorway	MJ/km	2.6866	2.5405	
		Fuel2	Motorway	MJ/km	1.2752	1.2067	
	Calculated overall result (SE)	**Fuel1**	**All**	**MJ/km**	**1.9926**	**1.8842**	
		Fuel2	**All**	**MJ/km**	**0.7204**	**0.6817**	
5	**Energy cons. share (by road)**	All	All	TC Range km	60	70	
	Calculated	All	All	TC / RW MJ/km	1.161	1.156	(7)
	Calculated	All	All	RW Range km	52	61	(8)
	Calculated	All	Urban	RW Range km	15	16	(9)
	Calculated	All	Rural	RW Range km	27	29	(9)
	Calculated	All	Motorway	RW Range km	4	4	(9)
	Calculated from UF	All	All	% elec km RW	75%	80%	(8)
	Calculated from UF, road priority	All	Urban	% elec km RW	75%	80%	(9)
	Calculated from UF, road priority	All	Rural	% elec km RW	75%	80%	(9)
	Calculated from UF, road priority	All	Motorway	% elec km RW	75%	80%	(9)
6	**Final energy cons.**	Fuel1	Urban	%Share	25.0%	20.0%	
		Fuel2	Urban	%Share	75.0%	80.0%	
		Fuel1	Rural	%Share	25.0%	20.0%	

#	Step	Fuel	Road	Parameter	2020	2030*	Note
		Fuel2	Rural	%Share	75.0%	80.0%	
		Fuel1	Motorway	%Share	25.0%	20.0%	
		Fuel2	Motorway	%Share	75.0%	80.0%	
		Fuel1	All	%Share	25.0%	20.0%	
		Fuel2	All	%Share	75.0%	80.0%	
	Calculated final result (SE)	**Fuel1**	**Total**	**MJ/km**	**0.4981**	**0.3768**	
		Fuel2	**Total**	**MJ/km**	**0.5403**	**0.5454**	

Notes: * similarly for other future time periods; *Key*: Fuel1 = Gasoline; Fuel2 = Electricity.

#	Comment
(1)	Mass change calculated based on a larger battery capacity needed when moving from the default electric range (50km in 2020) to high electric range scenario (60km in 2020).
(2)	%Energy/Mass = the % change in energy consumption for every % change in the total vehicle mass.
(3)	Loading factor mass impacts are only relevant to heavy duty freight vehicles – i.e. rigid and artic lorries
(4)	The average temperature difference between the selected country and the EU average (for information)
(5)	Impacts on energy consumption are calculated relative to a default 100% value for 20ºC for differences in the average annual ambient temperature for the selected country/region (in this case 2ºC for Sweden) or for a specific temperature sensitivity (e.g. -10 ºC) versus the default EU average (~10ºC) for electric or ICE operation. For example, the ICE impact for SE vs EU = (% change SE vs 20ºC) – (% change EU vs 20ºC)
(6)	%Av. MJ/km = the energy consumption when operating on a particular road type/speed relative to the overall EU average MJ/km.
(7)	This is the revised differential between the regulatory Test-Cycle (TC) energy consumption per km, and the calculated real-world (RW) average based on all the subsequent adjustments made in the calculations.
(8)	Real-world (RW) electric range adjusted to account for the higher electricity consumption versus the regulatory test-cycle upon which the initial electric range was defined.
(9)	The LCA modelling calculations have the option to prioritise electric operation onto urban roads; however, by default it is assumed the electric operation is evenly distributed on the different road types based on their respective share of overall km.

Key data sources and assumptions

Relevant high-quality information/data was already available in most cases from pre-existing studies for the Commission by Ricardo and others, or in standardised international emissions inventory methodologies (such as COPERT, see later Box 14), that were used as a basis for the assumptions. However, the key exception is energy consumption for new electrified powertrain heavy-duty vehicles, which have only recently begun to be developed or introduced into the marketplace. For these, Ricardo utilised a limited internal simulation exercise (based on pre-existing models/cycle definitions and using standard VECTO regulatory cycles) to estimate the relative performance (compared to reference diesel equivalents) of a selection of gas, hybrid and electric powertrain vehicle types for each of the four HDV vehicle categories for the LCA.

Additional information was also utilised from work by Ricardo for the UK Department for Transport on speed-emission/energy consumption relationships for alternative powertrain vehicles (Ricardo Energy & Environment, 2015).

A3.13.3.2 Vehicle direct emissions

The considerations for direct operational emissions from the vehicle are similar to those for energy consumption. Emissions can be broadly categorised into three types, using the following methodology:

1. *Tailpipe (exhaust) emissions of CO_2 and SO_2:* which can be calculated based directly based on the carbon and sulphur content of the fuels and the total energy consumption. Separate tracking for fossil and biogenic/sequestered carbon content has been provided also.
2. *Other tailpipe (exhaust) emissions:* These include air pollutants such as NOx (NO, NO_2), PM (PM_{10}, $PM_{2.5}$), etc., as well as certain GHG (i.e. CH_4 and N_2O). These emissions are calculated based on the same inventory methods as for the energy consumption aspects, i.e. using relevant COPERT speed-emission curves for the most recent Euro standards for new vehicles. These speed-emission curves include accounting for real-world effects and also allow for variations in emissions by road type/speed to be incorporated (where available). This methodology also allows for the calculation of region-specific emissions estimates through variations in the share of driving on different road types.
3. *Non-tailpipe emissions*: These emissions include tyre & brake wear, road wear and particulate resuspension. They have also been estimated using the relevant inventory-based methodologies, as already applied by Ricardo in the development of the UK's National Atmospheric Emissions Inventory (NAEI) (BEIS, 2020).

From the perspective of temporal considerations, current inventory methods already provide speed-emission curves (or static assumptions for certain pollutants) for all current/established future regulatory standards. However, it is unclear how future regulations in this area, and developments in emissions reduction technology, might change. The default approach was therefore to utilise estimates based on the inventory methods relating to the most current regulatory standards. A sensitivity on potential future improvements has also been included, as discussed in the main report.

Box 13: Additional commentary on the developed approach

The majority of stakeholders consulted during the project agreed with the proposed approach to estimate direct vehicle emissions based on inventory approaches covering existing regulatory standards. However, no suitable method for accounting for potential future improvements was found.

The best option identified was therefore to conduct a sensitivity on potential future improvements, but leave impacts derived based on current regulatory requirements as the default up to 2050. The sensitivity assumptions utilised have been summarised in the main report.

Key data sources and assumptions

The primary data source used to calculate emissions were speed-emission curves from COPERT (also used in the UK NAEI), which cover all conventional powertrain vehicles and also a range of alternative powertrains. These were supplemented, to fill gaps, also with data based on analysis Ricardo completed for the UK Department for Transport on speed-emission/energy consumption relationships for alternative powertrain vehicles (Ricardo Energy & Environment, 2015). A summary of the COPERT model and methodology is provided also in Box 14 below also.

Box 14: Summary of the COPERT model and methodology

Summary

The COPERT methodology and software (http://www.emisia.com/copert/General.html) represent the most widespread approach in calculating emissions from road transport in Europe. Most of the EU-27 Member States are using COPERT for compiling their national emissions inventories and submitting to different international protocols and conventions (such as NECD, CLRTAP, UNFCCC, etc.) in accordance to their obligations. The COPERT methodology is rated as the most detailed Tier 3 methodology for emissions calculations, with emissions factors being based mainly upon a combination of real-world and laboratory vehicle testing on real-world cycles for most vehicle types.

Background

COPERT stands for COmputer Programme to calculate Emissions from Road Transport and has a development history that dates back to 1988. In these 25 years of development, a large number of methodological and software revisions have taken place. In total, six major versions of COPERT have been produced, namely COPERT 85 (1998), COPERT 90 (1992), COPERT II (1995), COPERT III (2000), COPERT 4 (2006) and COPERT 5 (2016).

The development of COPERT is coordinated by the European Environment Agency (EEA), in the framework of the activities of the European Topic Centre on Air pollution, Transport, Noise, and Industrial pollution (ETC/ATNI). The European Commission's Joint Research Centre manages the scientific development of the model.

The COPERT methodology is part of the EMEP/EEA air pollutant emission inventory guidebook for the calculation of air pollutant emissions and is consistent with the 2006 IPCC Guidelines for the calculation of greenhouse gas emissions. The use of a software tool to calculate road transport emissions (and energy consumption) allows for a transparent and standardized, hence consistent and comparable data collecting and emissions reporting procedure, in accordance with the requirements of international conventions and protocols and EU legislation.

Technical features

COPERT estimates emissions (and fuel consumption) from all relevant road vehicle operation modes:

- thermal stabilised engine operation ('hot' emissions);
- the warming-up phase ('cold start' emissions);
- non-exhaust emissions (from fuel evaporation, tyre and brake wear emissions).

COPERT contains emission (and fuel consumption) factors for more than 450 individual vehicle types including for:

- passenger cars;
- light commercial vehicles;
- heavy duty vehicles (including trucks and buses);
- L-category vehicles (including mopeds, motorcycles, quads and mini-cars).

COPERT is often classified as an 'average speed' model; this refers to specific parts of the software, primarily hot emission factors (g/vkm) and fuel consumption, which are a function of the mean travel speed. However, other detailed sub models are included that are not a function of average speed (e.g. evaporative emissions). In general, the model is based on comprehensive laboratory emission tests over various drive cycles (hot running/cold start) or test procedures (evaporative) or derived from other methods (e.g. 'apparent' metal emissions, non-exhaust PM emissions).

To date the emission factors of COPERT have been largely based on large empirical test programs. In this approach, numerous vehicles are driven over real-world drive cycles on a chassis dynamometer with simultaneous modal or 'bag' emission measurements. Over the last 4-5 years PEMS tests are increasingly being used for complementing the emission factors development. Mean emission factors (g/km) are then related to the average speeds of (predefined) cycle segments through model fitting procedures. It is noted that other approaches (SHED test, near-road air quality measurements, literature review etc.) are used for specific sub models in the software such as evaporative emissions, non-exhaust PM emissions (tyre, brake, road) and heavy metal emission factors.

For alternative fuel powertrains (e.g. LPG, CNG, LNG) there are fewer real-world and laboratory test data available compared to petrol and diesel vehicles, however numbers are increasing. For new powertrains, again there is a relatively small (but increasing) sample of vehicles tested, and so relying modelling/simulation is currently used to fill the gap, with the results of the tests used to calibrate and validate the developed vehicle models (such as PHEVs for example).

Other applications

In addition to emissions inventories (see above), COPERT has been used by many institutions for future scenario modelling and projections. It has been extensively used for high level policy assessment at the EU level (e.g. in the PRIMES-TREMOVE model used to inform many EC transport impact assessments), trend analysis, and input for air quality modelling and impact assessment studies, either directly or after some modifications, sometimes in combination with other emission models. Apart from inventorying applications, projections, and impact analysis studies, there are many other applications of COPERT, including tunnel studies, academic research and use for lectures/courses/theses, emissions and emission factors estimates, and more.

Source: Summary provided by Giorgos Mellios, Emisia (2020).

A3.13.3.3 Activity and lifetime

For vehicle activity and mileage, an age-dependant activity (i.e. annual mileage) profile was used, based on the most recent evidence on this from Commission studies and modelling, and calibrated to total lifetime activity/years. In addition, the EU average activity was split by road type (i.e. by urban /rural /motorway share of total km) by vehicle type based on EC modelling datasets (see earlier section).

Sensitivities were also included on the lifetime mileage, and on variation in (regional) mileage by road type, to account for variations in use (regional or otherwise). In particular, for heavy duty vehicles the analysis also factored in the relevant regulatory duty cycles for the vehicle types modelled, where relevant (i.e. as set out in earlier Table A25).

Additional accounting for vehicle loading (that feeds into the calculation of real-world energy consumption – see Section A3.13.3.1) is also provided for freight vehicles.

Key sources of assumptions for vehicle activity and lifetime:

The datasets available on vehicle lifetime mileage and its age-dependant profile for light duty vehicles will be based upon recent studies in this area including (Ricardo-AEA, 2014a), (TML et al, 2016) and (CE Delft et al., 2017) (see also Appendix A4 for details). For heavy-duty lorries, where there is also less robust information available, variations in the average over time are likely to also reflect changes in typical duty cycles for larger vehicles; for these the age-dependent profiles were based on analysis of datasets developed for EU transport modelling from (Emisia, 2013).

A3.13.3.4 Vehicle maintenance and component replacement

It was concluded from the literature that maintenance (excluding traction battery replacement) does not account for a large share of the overall environmental impacts in the vehicle life cycle and thus a simplified approach for dealing with maintenance was expected to be sufficient.

Impacts from vehicle maintenance and component replacement were therefore characterised based on the typical replacement frequency (in 1000s of km) for the following key components and consumables for different vehicle types, and the corresponding production impacts for these:

- Tyres
- Transmission/gearbox fluid
- Screenwash
- Engine lubricating oil
- Coolant
- Exhaust and aftertreatment system
- AdBlue use (based on fuel consumption for diesel vehicles)

For vehicle traction batteries, the majority of experts consulted agreed with the approach for accounting for the frequency of energy storage replacement based on a combination of parameters including the anticipated battery cycle life (i.e. number full charge/discharge cycles). This enabled a dynamic link to the assumptions on battery sizing/electric range and the lifetime mileage (and the sensitivities also conducted on these elements). The technical performance of batteries with regards to cycle life are likely evolve (improve) over time, which was also factored into the analysis (see Appendix A4 for further information on the assumptions used in the application of the LCA methodology).

The methodology for determining replacements is as follows:

$$\boldsymbol{N} = \frac{(\mathbf{E}\ [\text{Average}] \times \mathbf{A}\ [\text{Lifetime}])}{(\boldsymbol{C}\ [Battery\ usable] \times \boldsymbol{CL}\ [Battery])}$$

Where

N = Total number of traction batteries needed over the vehicle lifetime

C [Battery usable] = usable traction battery capacity in kWh (to be defined based on the electric range)

CL [Battery] = average battery cycle life – number of full charge/discharge cycles

A [Lifetime] = vehicle lifetime activity (in km)

E [Average] = vehicle average electrical energy consumption, in kWh per km

All of these parameters are anticipated to either be variable over the time-horizon set for the analysis (i.e. to 2050) and/or their variation will be explored through sensitivities.

As a refinement, a calculation to determine the potential need for a fuel cell replacement was also characterised on a similar basis, using the average power rating, kWh demand from the vehicle activity and energy consumption and lifetime in hours for the fuel cell.

Box 15: Additional commentary on the developed approach

The majority of stakeholders agreed with the proposed approach to estimate the number of battery replacements. Some stakeholders suggested adding even more complexity (e.g. accounting for depth-of-discharge, other impacts affecting lifetime), but these are not judged by us to be practical/proportionate for this study. Others also suggested a more simplified approach.

There was a less conclusive result on whether a similar methodology should be employed also for fuel cells; however information was available of current and projected operational life in hours, and so a similar methodology was also adopted for these, for consistency.

Key data sources and assumptions

Most of the data used in the calculation of the number of replacements (i.e. activity, battery capacity, etc.) is already taken from other parts of the methodology. The key additional data assumption is the average battery cycle life. For this parameter, assumptions on current and potential future performance were based on a limited review of the available literature. For example, according to (FREVUE, 2017), the average anticipated cycle life for xEV batteries is 3000 cycles, with industry targeting 5000 cycles in the future - recently Prof. Jeff Dahn (Tesla's battery research partner) published an open access paper on a 'million mile battery' chemistry that has the potential to achieve over 5000 cycles (Green Car Congress, 2019). The initial assumptions for battery cycle life were reviewed internally with Ricardo's battery experts, and also by key expert stakeholders to further refine these assumptions as part of the data validation exercise (see Appendix A2.3).

A3.13.4 Vehicle end-of-life (EoL)

The general approach to end-of-life modelling has already been outlined in earlier Section A3.5. The default assumption is that the average vehicle has a full lifetime in the EU and is also recycled/disposed of in the EU at the end of its life. However, there are also additional specific considerations that will also be accounted for either as part of the default arrangements, or potentially through appropriate sensitivities, including:

- Accounting for future changes in recycling rates and recycling improvements (for key materials and xEV batteries).
- Accounting for Impacts from the potential future xEV battery second-life.

The proposed methodological approaches to dealing with these elements are discussed below.

A3.13.4.1 Accounting for future changes in recycling rates and recycling improvements

Whilst for many of the materials there are established recycling processes, for certain key materials (notably carbon fibre composites) and components (e.g. xEV batteries and fuel cells) these are still under development and are likely to improve/change significantly in future years.

For materials like carbon fibre composites (CarbonFRP), it is appropriate to utilise sensitivities, given the uncertainty in their future end-of-life treatment.

For xEV batteries, we adopted a more sophisticated approach to model their end fate (i.e. in a similar way to the additional detail also provided for battery production), summarised as follows: Currently, xEV battery recycling is at very low volumes and has not been optimised specifically for the automotive sector. As battery technology evolves, and deployment increases improvements in recycling techniques and processes are likely to follow. Such improvements were reflected in the end-of-life treatment of xEV battery recycling, by adapting currently available datasets from the GREET (ANL, 2018) and EverBatt models (ANL, 2018a) for different types of recycling processes. This analysis also factors in projected future improvements in material recovery rates, with a shift towards new hydrometallurgical process, and in process energy mix/use. Default and alternative 'EU Sustainable Value Chain (EUSVC) scenario assumptions were developed to explore potential sensitivities around this. Further details on the battery recycling assumptions are also provided in later Appendix A4.3.4.

A3.13.4.2 Accounting for the potential impacts of the second-use of xEV batteries

As discussed in earlier Section A3.5, the potential impact of second-use of xEV batteries is explored using a simplified methodology where a credit is applied, as illustrated below, as developed in (Ricardo Energy & Environment, 2019). Since the shares of xEV batteries that might go into second-life uses is highly uncertain, the assumptions here were based on best available information/understanding on the potential, with the uncertainty around this explored in a sensitivity on the assumptions:

$$\mathbf{SLC}\ [battery] = \boldsymbol{RS}\ [battery] \times \boldsymbol{SL}\ [battery] \times \boldsymbol{MC}\ [battery]$$

Where

SLC [battery] = net second-life credit for xEV batteries, as a % of a new battery

RS [battery] **=** average % share of xEV batteries suitable for repurposing for second-use applications following the end of their first use in the xEV

SL [battery] **=** average remaining lifetime of xEV batteries repurposed for second-use, as a % of the lifetime of an equivalent new battery used instead in the second-use application.

MC [battery] **=** possible additional market constraint factor (e.g. in case the potential supply of second-life batteries is greater than the natural market requirements for energy storage), %

A4 Appendix 4: Additional details from the application of the LCA methodology

This Appendix provides a range of additional details from the application of the LCA methodology, including a high-level summary of the data sources used in the calculations, as well as a selection of tables and charts with information on some of the key assumptions and input data.

Further information is also available in the 'Vehicle LCA Results Viewer' presented alongside this report.

A4.1 Background LCI and data

This Appendix subsection provides a summary of some of the background LCI and other key data and assumptions for the overall vehicle cycle that were used in the application of the LCA methodology to derive the results shown in the main report.

Table A27 provides an assessment of the quality and basis of the background LCI materials dataset, and Table A28 provides a summary of the materials and process extracted from the reference LCI databases (principally Ecoinvent, and the GREET model in the case of certain missing materials).

Table A27: Additional detail on the basis and quality of the background LCI materials dataset

High	Medium	Low	N/A

Material	Virgin /Primary	Recycled /Secondary	Processing	Energy Recovery	Disposal
General materials					
Iron & Steel	H (1)	H (1)	M (2)	N/A	H (1)
Aluminium	H (1)	H (1)	M (2)	N/A	M (2)
Copper	H (1)	H/M (1)	M (2)	N/A	M (2)
Other metals	H (1)	M/L (3)	L (*)	N/A	M (2)
Plastics	H (1)	M (2)	L (*)	H/M (4)	H/M (2)
CarbonFRP, Carbon FRP (HPV)	H/M (5)	M/L (3)	H/M (5)	H/M (4)	M (2)
Textiles	M (1)	M/L (1)	L (*)	H/M (4)	M (4)
Other materials	H (1)	M/L (3)	L (*)	M (4)	M (4)
Electronics	M (1)	M/L (1)	N/A	N/A	H/M (2)
Additional materials for battery manufacturing and recycling					
Materials used in batteries	H (1), (5)	N/A	N/A	M (4)	M (4)
Materials used in battery manufacturing and recycling processes	H (1), (5)	N/A	N/A	M (4)	M (4)

Sources: * No data available on the impacts of transforming materials into finished products.

#	Source	Quality	Comment
(1)	Ecoinvent	High to Medium	In many cases datasets sourced from Ecoinvent were specific to the material / activity in question, e.g. primary or secondary material, disposal of a specific material, etc. In a few cases the 'materials' concerned groups covering a very broad range of different materials that are likely to have quite wide-ranging and different impacts, such as for textiles, and particularly for electronic components where a very wide range of options exist.

#	Source	Quality	Comment
(2)	Ecoinvent	Medium	In some cases impact datasets sourced from Ecoinvent were more generic, or approximations had to be made based on a potentially diverse range of possible activities. For example, (1) there are generic processing of materials like steel, aluminium and copper into components, but a range of possible impacts from manufacturing components from these materials is likely in reality (depending on the component). (2) In addition it was necessary to use some specific material impact factors (e.g. for recycling or disposal of similar types of materials such as plastics or metals) to estimate the impacts also for other similar groups of similar materials, where a specific factor does not exist/could not be identified, e.g. the impact factors for scrap steel disposal was used for most structural metals.
(3)	Ricardo (2019)	Medium /Low	There was limited availability of data on the impacts for producing secondary /recycled materials in Ecoinvent, so in many cases it was necessary to make (generally very conservative) assumptions for the lower impacts of these compared to virgin materials. These were made either based on information identified in the literature, or comparing the differences to materials where virgin and secondary material datasets were available.
(4)	(Environment Agency, 2010)	High /Medium	Information on the LHV (lower heating value) of key material types were based on information from the UK Environment Agency's WRATE model for the purposes of calculating the energy produced in incineration/energy recovery processes.
(5)	GREET (ANL, 2018)	High /Medium	In cases where datasets were not available in Ecoinvent, they were generally sourced from the GREET model. The main limitation here was that data were generally only available for specific (mostly air quality) pollutant emissions, so did not cover all the impact categories used in this study.

Table A28: Summary on the source for key background LCI materials dataset

Material/Component	Type	Source	Listed process from source
General primary (virgin) materials			
Steel (unalloyed)	Virgin	Ecoinvent 3/SimaPro	Steel, unalloyed {GLO}| market for | APOS, U
Steel (low alloy)	Virgin	Ecoinvent 3/SimaPro	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | APOS, U
Steel (high alloy)	Virgin	Ecoinvent 3/SimaPro	Steel, chromium steel 18/8 {GLO}| market for | APOS, UU
Iron	Virgin	Ecoinvent 3/SimaPro	Iron pellet {GLO}| market for | APOS, U
Iron (cast)	Virgin	Ecoinvent 3/SimaPro	Pig iron {GLO}| market for | APOS, U
Ferrite	Virgin	Ecoinvent 3/SimaPro	Ferrite {GLO}| market for | APOS, U
Aluminium	Virgin	Ecoinvent 3/SimaPro	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | APOS, U
Lithium	Virgin	Ecoinvent 3/SimaPro	Lithium {GLO}| market for | APOS, U
Magnesium	Virgin	Ecoinvent 3/SimaPro	Magnesium {GLO}| market for | APOS, U
Titanium	Virgin	Ecoinvent 3/SimaPro	Titanium, primary {GLO}| market for | APOS, U
Brass	Virgin	Ecoinvent 3/SimaPro	Brass {CH}| market for brass | APOS, U
Cobalt	Virgin	Ecoinvent 3/SimaPro	Cobalt {GLO}| market for | APOS, U
Copper	Virgin	Ecoinvent 3/SimaPro	Ricardo Copy Copper {GLO}| market for | APOS, U - Primary
Lead	Virgin	Ecoinvent 3/SimaPro	Lead {GLO}| market for | APOS, U
Manganese	Virgin	Ecoinvent 3/SimaPro	Manganese {GLO}| market for | APOS, U
Nickel	Virgin	Ecoinvent 3/SimaPro	Nickel, 99.5% {GLO}| market for | APOS, U
Zinc	Virgin	Ecoinvent 3/SimaPro	Zinc {GLO}| market for | APOS, U
Gold	Virgin	Ecoinvent 3/SimaPro	Gold {GLO}| market for | APOS, U
Palladium	Virgin	Ecoinvent 3/SimaPro	Palladium {GLO}| market for | APOS, U
Platinum	Virgin	Ecoinvent 3/SimaPro	Platinum {GLO}| market for | APOS, U
Rhodium	Virgin	Ecoinvent 3/SimaPro	Rhodium {GLO}| market for | APOS, U
CarbonFRP	Virgin	GREET	Carbon Fiber Composite Plastic for General Use

Material/Component	Type	Source	Listed process from source
CarbonFRP (HPV)	Virgin	GREET	Carbon Fiber Composite Plastic for High Pressure Vessels
GlassFRP	Virgin	Ecoinvent 3/SimaPro	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | APOS, U
Plastic: Average	Virgin	Ecoinvent 3/SimaPro	Average Plastic
Plastic: PE	Virgin	Ecoinvent 3/SimaPro	Polyethylene, linear low density, granulate {GLO}| market for | APOS, U
Plastic: PP	Virgin	Ecoinvent 3/SimaPro	Polypropylene, granulate {GLO}| market for | APOS, U
Rubber/Elastomer	Virgin	Ecoinvent 3/SimaPro	Synthetic rubber {GLO}| market for | APOS, U
Silicone product	Virgin	Ecoinvent 3/SimaPro	Silicone product {RER}| market for silicone product | APOS, U
AdBlue	Virgin	Ecoinvent 3/SimaPro	Adblue
Coolant: Ethylene Glycol	Virgin	Ecoinvent 3/SimaPro	Ethylene glycol {RER}| production | APOS, U
Coolant: Propylene Glycol	Virgin	Ecoinvent 3/SimaPro	Propylene glycol, liquid {RER}| market for propylene glycol, liquid | APOS, U
Lubricating Oil	Virgin	Ecoinvent 3/SimaPro	Lubricating oil {RER}| market for lubricating oil | APOS, U
Screenwash	Virgin	Ecoinvent 3/SimaPro	Screenwash
Water	Virgin	Ecoinvent 3/SimaPro	Water, completely softened, from decarbonised water, at user {GLO}| market for | APOS, U
Carbon Paper	Virgin	Ecoinvent 3/SimaPro	Activated carbon, granular {RER}| activated carbon production, granular from hard coal | APOS, U
Glass	Virgin	Ecoinvent 3/SimaPro	Flat glass, uncoated {GLO}| market for | APOS, U
Graphite/Carbon	Virgin	Ecoinvent 3/SimaPro	Graphite, battery grade {CN}| production | APOS, U
Nd(Dy)FeB	Virgin	Ecoinvent 3/SimaPro	Permanent magnet, for electric motor {GLO}| market for permanent magnet, electric passenger car motor | APOS, U
Textiles	Virgin	Ecoinvent 3/SimaPro	Textile, woven cotton {GLO}| market for | APOS, U
Thermal Insulation	Virgin	Ecoinvent 3/SimaPro	Glass wool mat {GLO}| market for | APOS, U
Wood	Virgin	Ecoinvent 3/SimaPro	Plywood, for indoor use {RER}| market for | APOS, U
Electronic Parts	Virgin	Ecoinvent 3/SimaPro	Electronics, for control units {GLO}| market for | APOS, U
Materials used to define 'Resin: Average'			
Epoxy resin	Virgin	Ecoinvent 3/SimaPro	Epoxy resin, liquid {RER}| market for epoxy resin, liquid | APOS, U

Material/Component	Type	Source	Listed process from source
Methacrylate ester resin	Virgin	Ecoinvent 3/SimaPro	Methyl methacrylate {RER}| market for methyl methacrylate | APOS, U
Phenolic resin	Virgin	Ecoinvent 3/SimaPro	Phenolic resin {RER}| market for phenolic resin | APOS, U
Polyester resin	Virgin	Ecoinvent 3/SimaPro	Polyester resin, unsaturated {RER}| market for polyester resin, unsaturated | APOS, U
Materials used to define 'Plastic: Average'			
Plastic: ABS	Virgin	Ecoinvent 3/SimaPro	Acrylonitrile-butadiene-styrene copolymer {RER}| production | APOS, U
Plastic: PA/Nylon 6	Virgin	Ecoinvent 3/SimaPro	Nylon 6 {GLO}| market for | APOS, U
Plastic: PA/Nylon 66	Virgin	Ecoinvent 3/SimaPro	Nylon 6-6 {RER}| production | APOS, U
Plastic: PC	Virgin	Ecoinvent 3/SimaPro	Polycarbonate {RER}| production | APOS, U
Plastic: PET	Virgin	Ecoinvent 3/SimaPro	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U
Plastic: PFSA	Virgin	Ecoinvent 3/SimaPro	Perfluoropentane {GLO}| market for | APOS, U
Plastic: PPS	Virgin	Ecoinvent 3/SimaPro	Polyphenylene sulfide {GLO}| market for | APOS, U
Plastic: PS	Virgin	Ecoinvent 3/SimaPro	Polystyrene foam slab {RER}| production | APOS, U
Plastic: PUR	Virgin	Ecoinvent 3/SimaPro	Polyurethane, flexible foam {RER}| market for polyurethane, flexible foam | APOS, U
Materials used to define 'Misc Other'			
Antimony	Virgin	Ecoinvent 3/SimaPro	Antimony {GLO}| market for | APOS, U
Solder	Virgin	Ecoinvent 3/SimaPro	Solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry {GLO}| market for | APOS, U
Tin	Virgin	Ecoinvent 3/SimaPro	Tin {RER}| production | APOS, U
Doped Silicon	Virgin	Ecoinvent 3/SimaPro	Single-Si wafer, for electronics {RER}| production | APOS, U
Glass fibre	Virgin	Ecoinvent 3/SimaPro	Glass fibre {GLO}| market for | APOS, U
Silica sand	Virgin	Ecoinvent 3/SimaPro	Silica sand {RoW}| production | APOS, U
Aluminium oxide	Virgin	Ecoinvent 3/SimaPro	Aluminium oxide {GLO}| market for | APOS, U
Enamel	Virgin	Ecoinvent 3/SimaPro	Enamelling {GLO}| market for | APOS, U
Zinc oxide	Virgin	Ecoinvent 3/SimaPro	Zinc oxide {RER}| production | APOS, U

Material/Component	Type	Source	Listed process from source
General secondary (recycled) materials			
Steel (low alloy)	Recycled	Ecoinvent 3/SimaPro	Steel, low-alloyed {RER}| steel production, electric, low-alloyed | APOS, U
Aluminium (cast)	Recycled	Ecoinvent 3/SimaPro	Aluminium, cast alloy {RER}| treatment of aluminium scrap, new, at refiner | APOS, U
Aluminium (wrought)	Recycled	Ecoinvent 3/SimaPro	Aluminium scrap, new {RER}| treatment of, at refiner | APOS, U
Copper	Recycled	Ecoinvent 3/SimaPro	Copper, blister-copper {RER}| production | APOS, U
Lead	Recycled	Ecoinvent 3/SimaPro	Lead {RER}| treatment of scrap acid battery, remelting | APOS, U
Wood	Recycled	Ecoinvent 3/SimaPro	Waste wood, untreated {RER}| market group for waste wood, untreated | APOS, U
Plastic: Average	Recycled	Ecoinvent 3/SimaPro	Polyethylene terephthalate, granulate, amorphous {RoW}| polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate | APOS, U
Electronics	Recycled	Ecoinvent 3/SimaPro	Used capacitor {GLO}| market for | APOS, U
Lubricating Oil	Recycled	Ecoinvent 3/SimaPro	Waste mineral oil {Europe without Switzerland}| market for waste mineral oil | APOS, U
Glass	Recycled	Ecoinvent 3/SimaPro	Glass cullet, sorted {RER}| treatment of waste glass from unsorted public collection, sorting | APOS, U
Textiles	Recycled	Ecoinvent 3/SimaPro	Sodium sulfate, anhydrite {GLO}| textile production, woven cotton | APOS, U
Other processes			
Diesel	Energy	Ecoinvent 3/SimaPro	Diesel {Europe without Switzerland}| market for | APOS, U
LPG	Energy	Ecoinvent 3/SimaPro	Liquefied petroleum gas {RoW}| market for | APOS, U
Hard Coal	Energy	Ecoinvent 3/SimaPro	Coke {GLO}| market for | APOS, U
Heat (from natural gas)	Energy	Ecoinvent 3/SimaPro	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | APOS, U
Steel (low alloy)	Intermediate	Ecoinvent 3/SimaPro	Metal working, average for steel product manufacturing {RER}| processing | APOS, U
Steel (high alloy)	Intermediate	Ecoinvent 3/SimaPro	Metal working, average for chromium steel product manufacturing {RER}| processing | APOS, U
Aluminium	Intermediate	Ecoinvent 3/SimaPro	Metal working, average for aluminium product manufacturing {RER}| processing | APOS, U
Copper	Intermediate	Ecoinvent 3/SimaPro	Wire drawing, copper {RER}| processing | APOS, U

Material/Component	Type	Source	Listed process from source
Steel (low alloy)	EnRecovery	Ecoinvent 3/SimaPro	Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | APOS, U
Plastic: Average	EnRecovery	Ecoinvent 3/SimaPro	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, municipal incineration | APOS, U
Rubber/Elastomer	EnRecovery	Ecoinvent 3/SimaPro	Waste rubber, unspecified {Europe without Switzerland}| treatment of waste rubber, unspecified, municipal incineration | APOS, U
Misc Other	EnRecovery	Ecoinvent 3/SimaPro	Municipal solid waste {DE}| treatment of, incineration | APOS, U
Electricity from MSW	EnRecovery	Ecoinvent 3/SimaPro	Electricity, for reuse in municipal waste incineration only {GLO}| treatment of biowaste, municipal incineration | APOS, U
Heat from MSW	EnRecovery	Ecoinvent 3/SimaPro	Heat, for reuse in municipal waste incineration only {GLO}| treatment of biowaste, municipal incineration | APOS, U
Steel (low alloy)	Disposal	Ecoinvent 3/SimaPro	Scrap steel {Europe without Switzerland}| treatment of scrap steel, inert material landfill | APOS, U
Plastic: Average	Disposal	Ecoinvent 3/SimaPro	Waste plastic, mixture {Europe without Switzerland}| treatment of waste plastic, mixture, sanitary landfill | APOS, U
Lubricating Oil	Disposal	Ecoinvent 3/SimaPro	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration | APOS, U
Misc Other	Disposal	Ecoinvent 3/SimaPro	Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill | APOS, U
Electronics	Disposal	Ecoinvent 3/SimaPro	Electronics scrap {GLO}| market for | APOS, U
Water	ImpactFactor	Ecoinvent 3/SimaPro	H2O emissions
NMP	ImpactFactor	Ecoinvent 3/SimaPro	NMP Emissions
Rail freight transport	Transport	Ecoinvent 3/SimaPro	Transport, freight train {RER}| market group for transport, freight train | APOS, U
Road freight transport	Transport	Ecoinvent 3/SimaPro	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, U
Inland shipping freight transport	Transport	Ecoinvent 3/SimaPro	Transport, freight, inland waterways, barge tanker {RER}| processing | APOS, U

Material/Component	Type	Source	Listed process from source
Maritime shipping freight transport	Transport	Ecoinvent 3/SimaPro	Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U
Additional materials for battery manufacturing and recycling			
Aluminium Sulphate	Virgin	Ecoinvent 3/SimaPro	Aluminium sulfate, powder {RER}| market for aluminium sulfate, powder | APOS, U
Ammonia	Virgin	Ecoinvent 3/SimaPro	Ammonia, liquid {RER}| market for | APOS, U
Diammonium Phosphate	Virgin	Ecoinvent 3/SimaPro	Nitrogen fertiliser, as N {RER}| diammonium phosphate production | APOS, U
Electrolyte: Dimethyl Carbonate	Virgin	Ecoinvent 3/SimaPro	Dimethyl carbonate {GLO}| market for dimethyl carbonate | APOS, U
Electrolyte: Ethylene Carbonate	Virgin	Ecoinvent 3/SimaPro	Ethylene carbonate {GLO}| market for | APOS, U
Hydrochloric Acid	Virgin	Ecoinvent 3/SimaPro	Hydrochloric acid, without water, in 30% solution state {RER}| market for | APOS, U
Hydrogen Peroxide	Virgin	Ecoinvent 3/SimaPro	Hydrogen peroxide, without water, in 50% solution state {RER}| market for hydrogen peroxide, without water, in 50% solution state | APOS, U
LiPF6	Virgin	Ecoinvent 3/SimaPro	Lithium hexafluorophosphate {RoW}| production | APOS, U
Lime (CaO)	Virgin	Ecoinvent 3/SimaPro	Lime {RER}| market for lime | APOS, U
Lithium Carbonate	Virgin	Ecoinvent 3/SimaPro	Lithium carbonate {GLO}| market for | APOS, U
Lithium Hydroxide	Virgin	Ecoinvent 3/SimaPro	Lithium hydroxide {GLO}| market for | APOS, U
Manganese Oxide	Virgin	Ecoinvent 3/SimaPro	Manganese dioxide {GLO}| production | APOS, U
Manganese Sulphate	Virgin	Ecoinvent 3/SimaPro	Manganese sulfate {GLO}| production | APOS, U
Monoethanolamine	Virgin	Ecoinvent 3/SimaPro	Monoethanolamine {GLO}| market for | APOS, U
Nickel Sulphate	Virgin	Ecoinvent 3/SimaPro	Nickel sulfate {GLO}| production | APOS, U
NMP	Virgin	Ecoinvent 3/SimaPro	N-methyl-2-pyrrolidone {GLO}| market for | APOS, U
Oxygen	Virgin	Ecoinvent 3/SimaPro	Oxygen, liquid {RER}| market for | APOS, U
Phosphorus	Virgin	Ecoinvent 3/SimaPro	Phosphorus, white, liquid {GLO}| market for | APOS, U
Silicon	Virgin	Ecoinvent 3/SimaPro	Silicon, solar grade {RER}| silicon production, solar grade, modified Siemens process | APOS, U

Material/Component	Type	Source	Listed process from source
Sodium	Virgin	Ecoinvent 3/SimaPro	Sodium {GLO}| market for | APOS, U
Sodium Hydroxide	Virgin	Ecoinvent 3/SimaPro	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U
Sulphuric Acid	Virgin	Ecoinvent 3/SimaPro	Sulfuric acid {RER}| market for sulfuric acid | APOS, U
Ammonium Hydroxide	Virgin	GREET 2018	Ammonium Hydroxide
Cobalt Sulphate	Virgin	GREET 2018	Cobalt Sulfate (CoSO4)
Iron Oxide (Fe3O4)	Virgin	GREET 2018	Fe3O4 Production
Iron Sulphate	Virgin	GREET 2018	Iron Sulfate

Notes: Data was mainly extracted from GREET 2018 update (ANL, 2018); comparison with the 2019 update revealed no significant changes to the data utilised.

Table A29: Impact mid-point characterisation factors for vehicle exhaust/non-exhaust emission air pollutants

Pollutant	Full name	GWP, gCO_2eq	CED, MJ	AcidP, gSO_2eq	EutroP, gPO_4eq	POCP, gNMVOCeq	PMF, $gPM_{2.5}eq$
CO_2	Carbon monoxide	1	0.001	0	0	0	0
CH_4	Methane	36.75	0	0	0	0.0101	0
N_2O	Nitrous oxide	298	0	0	0.27	0	0
CO	Carbon monoxide	1.57	0.001	0	0	0.0456	0
NH_3	Ammonia	0	0.001	1.6	0.35	0	0.64
NMVOC	Non-Methane Volatile Organic Compounds	0	0	0	0	1	0.012
NO_x	Nitrogen oxides	0	0.001	0.5	0.13	1	0.88
*NO **	*Nitrogen oxide*	*0*	*0.001*	*0.5*	*0.13*	*1*	*0.88*
*NO_2 **	*Nitrogen dioxide*	*0*	*0.001*	*0.5*	*0.13*	*1*	*0.88*
PM_{10}	PM10	0	0	0	0	0	0
$PM_{2.5}$	PM2.5	0	0	0	0	0	1
SO_x	Sulphur oxides	0	0	1	0	0.0811	0.54
Pollutant	**Full name**	**HTP, CTUh/kg**	**ETP_FA, CTUe/kg**	**Other Impacts**			
PAH	Polyaromatic hydrocarbons	3.49E-08	0.1070	0			

Source: Impact factors extracted from SimaPro (2020) for the mid-point categories selected for this project.

Notes: Except for PAH, there are no impacts from the listed pollutants for the impact mid-points for ODP, IRP, HTP, ETP_FA, ARD_MM, ARD_FE, LandU, and WaterS. * NO and NO_2 are assumed to have the same impacts as NOx, in the absence of specific characterisation criterial for these.

A4.2 Electricity production chains

This Appendix subsection provides a summary of some of the key foreground data assumptions for the electricity production chains that were used in the application of the LCA methodology to derive the results shown in the main report.

A4.2.1 The ifeu Umberto electricity model

A4.2.1.1 Description of the applied electricity model

The applied electricity model (in Umberto 5.6) enables the calculations of all the above described scenarios and cases, which will be used to provide inputs to the Excel-based module.

A4.2.1.2 System boundary of the model

The **system boundary** of the entire module, as simplified in Figure A54, includes:

- the **power plant** processes for electricity generation using hard coal, brown coal (lignite), fuel oil, natural and derived gases, biomass (solid and biogas), nuclear, solar, hydro and wind power (both on- and off-shore),
- the upstream **fuel chains** (coal, lignite, natural gas, nuclear fuel, biomass),

- the **distribution** of electricity to the consumer with appropriate management and transformer losses[53] (note: Within this project not calculated in the electricity model itself but part of the vehicle LCA model).
- The production expenses of **capital goods** (mining infrastructure, power plants and distribution facilities) is optionally included (results can be calculated with or without capital goods).

As described in Appendix A3.6.2 the model allows allocation for electricity from **combined heat and power** (CHP) production. This can be adjusted according to the power plant type. An attribution of the burdens on electricity and district heating is performed through allocation based on exergetic conditions. The share of electricity is assigned an exergy value of $C_{el} = 1$, while the heat is evaluated using the so-called Carnot efficiency level.

In the Umberto model, the contributions from **waste incineration** are allocated to the waste sector and thus represent the supply of energy at “zero” ecological cost. Since the fuel is waste, all upstream processes (life cycle of the products ending up as waste in a municipal solid waste incinerator, MSWI) belong to the previous product lifecycle and are cut-off from the electricity production.

A4.2.1.3 Power plants, upstream fuel chains and distribution

In the following each module in the Umberto model is briefly described. Table A30 summarizes the input and output flows of the modules within the.

A4.2.1.3.1 Coal power plants (same principle for fuel oil power plants)

The emissions of all coal-fired power plants were calculated in accordance to BAT (Best Available Technology) reference documents and to actual emission reporting. However the calculation is modelled generically and takes fuel quality (content of sulphur and heavy metals) into account.

The actual power plant module is made up of individual modules which are drying/pulverizing coal, heating/boiler, exhaust gas cleaning components, electrostatic precipitators, flue gas desulfurization (FGD) and catalytic denitrification (DENOX). These sub-modules again require upstream supply of agents (such as limestone, ammonia), which are enclosed as input materials. These processes also lead to waste streams. Recovered wastes (e.g. inert granules or gypsum for building material) are cut-off, while non-recyclable waste in particular hazardous waste is deposed in landfills.

The boiler/steam-turbine system is a central sub-module, which include the settings for both, gross thermal and gross electric efficiencies. The reference flow is electricity (net) produced considering self-demand of the plant.

Additionally, in order to account for CCS (Carbon Capture and Storage) technologies, a further CCS-system can be chosen from the parametrisation. It assumes an average deposition rate for CO_2 of 90%. Furthermore, power plant efficiency drops by 12.5% points when applying CCS.

A4.2.1.3.2 Gas power plants

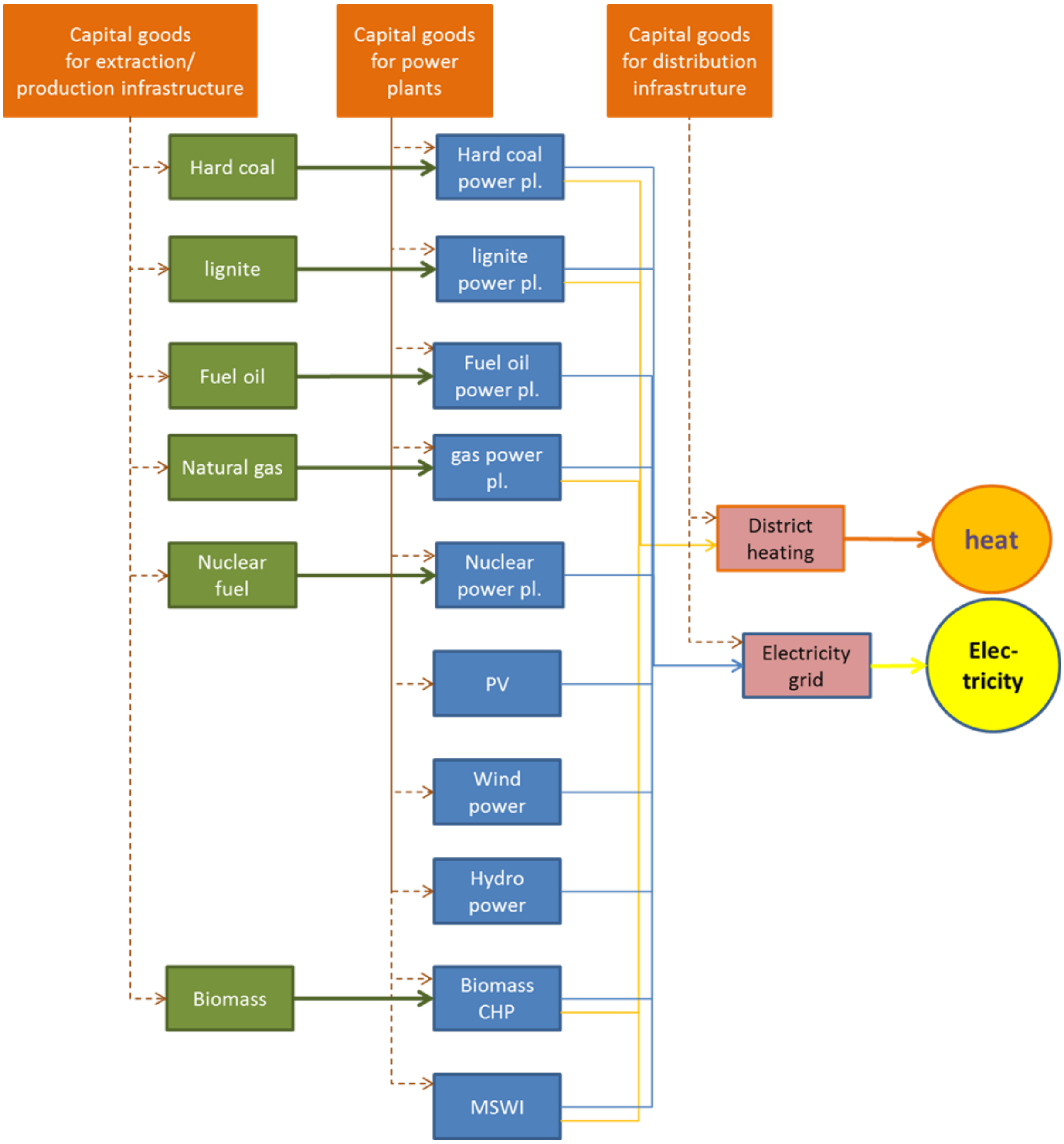
In contrast to coal-fired power plants, a gas-fired power plant does not have a complex exhaust gas purification system. On the other hand the technical typology is more diverse: steam turbine, gas turbine, combined cycle (GuD), gas engine – all these types are included within the model, leading to specific (but adjustable) efficiencies and emission rates for each type of gas power plant. A CCS-option is available for gas powered plants, too, following the above mentioned assumptions.

A4.2.1.3.3 Nuclear power plants

This module describes the average state of nuclear power plants in Europe based on the conditions during the early 90’s. The data is largely based on information from ecoinvent (based on Swiss power plants). The considered technologies are pressurized water reactors (PWR) and boiling water reactors (BWR). Background data for modelling are taken from IAEA (2009). The burn-up values are set at 6,375 MJ/kg of uranium for PWR and at 6,000 MJ/kg uranium for BWR. The gross electrical efficiency is set at 33 %. The model also includes the reprocessing and the final disposal.

[53] For the EU28, on average over the course of the study, transmission and distribution losses are 6.2% in the Baseline scenario and 5.2% in the TECH1.5 scenario

Figure A54: Schematic structure of the Umberto electricity model, subdivided into the modules fuel pre-chains (green), power plants (blue), distribution (lilac), capital goods (brown)



Source: ifeu illustration

Table A30: Reference flows (input output) of the power plant modules of the applied electricity model

Input/Output	Module	Specification of input
Input		
Fuel calculated considering the lower heating value corresponding to the thermal energy needed for the produced electricity (net)	Hard coal power plant	Hard coal
	Lignite power plant	Lignite
	Gas power plant	Natural gas (the model allows the inclusion of derived gases, such as blast furnace gas, coke oven gas or refinery gas)
	Fuel oil power plant	Fuel oil
	Nuclear power plant	Nuclear fuel rods
	Biomass CHP	Woody biomass substrates for biogas fermentation
	MSWI	Household waste
Water	All thermal power plants	Boiler feed, process water, cooling water.
Other material input	Coal, fuel oil, nuclear and biomass power plant	Auxiliary material for flue gas cleaning (e.g. lime, ammonia) or other processing
Output		
Electricity (net)	All power plants	Reference flow
Useful heat (in case the plants is actually exporting heat)	Coal, gas and biomass power plant	For district heating
Direct airborne emissions from stack	All thermal power plants	• Greenhouse gases (CO_2, N_2O, CH_4) • Classical air pollutants (SO_2, NO_x, CO, fine particles, etc.) • Heavy metals (As, Sb, Cd, Hg, etc.) • Organic pollutants (PAH, PCB, dioxins, etc.) • Radionuclides, measured in kilobecquerel (kBq)
Direct waterborne emissions from flue gas cleaning processes (in case wet scrubbing is applied)	Coal, fuel oil, nuclear and biomass power plant	• COD, BOD, nutrients (N, P) • Sulphate and other salts • Heavy metals (As, Sb, Cd, Hg, etc.) • Radionuclides, measured in kilobecquerel (kBq)
Other downstream processes		e.g. Landfills (including required transports until or from gate)

Notes: See later Table A32: in Section A4.2.2.2 for a summary of the Umberto electricity model output compatibility with the project's impact categories.

A4.2.1.3.4 Water, wind and geothermal power plant, photovoltaic systems

These power plants, based on renewable energy sources, are characterised by the absence of upstream fuel chains and beyond that have no significant upstream or downstream chains. A primary energy (renewable CED) to electrical energy ratio of 1:1 is assumed.

Infrastructure and capital goods for these plant, particularly wind turbines and PV systems are modelled on very recent data provided directly by manufactures.

A4.2.1.3.5 Biomass power plant

Two technology pathways are included in this module:

- Solid biomass (wood) in a power plant which is technically similar to coal power plants (steam turbine)
- Biogas plants (anaerobic digester), fed with crops (maize), biowaste and manure and the produced biogas converted in a CHP plant (gas engine) to electricity and heat.

A4.2.1.3.6 Waste incineration (MSWI)

This module describes the combustion of household waste in a plant that corresponds to a European state-of-the-art design (grate, heat recovery steam generators, and high standards of exhaust gas cleaning). The default settings refer to an average household waste with a heating value of 9 MJ/kg and a corresponding elemental analysis. The energy efficiency complies with the average European situation of 10 % net electricity and 30 % useful heat. The output corresponds to the already described solid-fuel-fired plants.

A4.2.1.3.7 Upstream fuel chains

The model includes for each fuel type a separate module (see Figure A54), covering the following process chains:

- Mining (fossil and nuclear fuels).
- Cultivation (wood or crops for biogas).
- Pre-processing, where needed, e.g. for natural gas, fuel oil (refinery) or nuclear fuel (enrichment, production of fuel elements).
- Transport, intermediate as well as the final transport to the power plant; in correspondence with specific origins: e.g. oversea shipment for coal or uranium ore; pipeline for natural gas.

A4.2.1.3.8 Distribution

The electricity undergoes transformer and distribution losses during the transportation from the power plant to the consumer. The amount of loss depends on the voltage level of the demanded electricity. For this study the model will adopt data for transmission and distribution losses from PRIMES modelling work, representing 6.5 % for the average of EU28 in 2020, improving to 3.2 % in 2050. Distribution and transmission within this project are not directly included in the ifeu electricity model but post processed within the vehicle LCA model.

A4.2.2 Background data

The electricity model utilises external datasets for the modelling of the background system. Table A31 summarizes the applied background data, indicating where in the model these data are used.

Table A31: Applied background data within the electricity model

Subject	Used in the model	Further specification	Data source
Hard coal mining	Upstream fuel module for *hard coal*	Cradle to gate submodules for coal from: • Western Europe (deep mining) • Eastern Europa (deep mining) • Russia (deep mining) • Colombia (surface mining) • USA (surface mining) • South Africa (surface mining) • China (deep mining) • Australia (surface mining)	ecoinvent 3.4 [(a)]

Subject	Used in the model	Further specification	Data source
Lignite mining	Upstream fuel module for *lignite*	one cradle to gate module representing European technology	ecoinvent 3.4 [(a)]
Natural gas production	Upstream fuel module for *natural gas*	Cradle to gate submodules for gas from: • Russia (on-shore, long distance pipeline) • Norway (off-shore) • The Netherlands (off-shore) • UK (off-shore) • Algeria (on-shore, LNG, long-distance pipeline) • Qatar (on-shore, LNG, shipping)	ecoinvent 2; [(a)] partially modified and updated by ifeu based on separate data research
Fuel oil production	Upstream fuel module for *fuel oil*	Aggregation of crude oil extraction, refining and transport; origin of crude oil average mix in Europe (North Sea, Russia, OPEC) Fuel oil as co-product from refinery	crude oil from ecoinvent 3.4 [(a)] refinery process by the ifeu refinery model
Nuclear fuel	upstream fuel module for *nuclear fuel*	Aggregation of mining, enrichment and production of fuel elements	ecoinvent 2 [(a)]
Woody biomass	upstream fuel module for biomass	Energy wood from forestry, chipped	calculation by ifeu
Maize	upstream fuel module for *biomass*	European (German) average data including fertilizer, land machine, harvesting and yield levels	BioEm, BioGrace
Transport	All upstream fuel modules Upstream fuel module for *natural gas*	Truck transport, shipping (various distances) Gas pipeline	TREMOD ecoinvent 2, [(a)] updated by ifeu based on Lechtenböhmer (2005)
Power plants	*hard coal power pl., lignite power pl., fuel oil power pl., biomass CHP*	Cradle to gate submodules for chemicals: lime, lime stone, caustic soda, ammonia, urea	ecoinvent 3.4 [(a)]
Infrastructure capital goods	All modules Wind power plant PV	Different steel alloys, copper, aluminium, cement, concrete Wind power plant construction PV modules	ecoinvent 3.4 [(a)] Including current data from producers (material bills)

Notes: (a) Above ecoinvent 3.5 was mentioned as reference for the description of divers LCIA categories (e.g. energy consumption, land use etc.) or the cut-off rule; the fact that the electricity model refers to ecoinvent 3.4 or even ecoinvent 2 with regard to the basic data does not lead to any inconsistencies since the latest update to ecoinvent version 3.5 doesn't affect the data sets utilized within the ifeu model and are thus consistent throughout.

A4.2.2.1 Foreground data

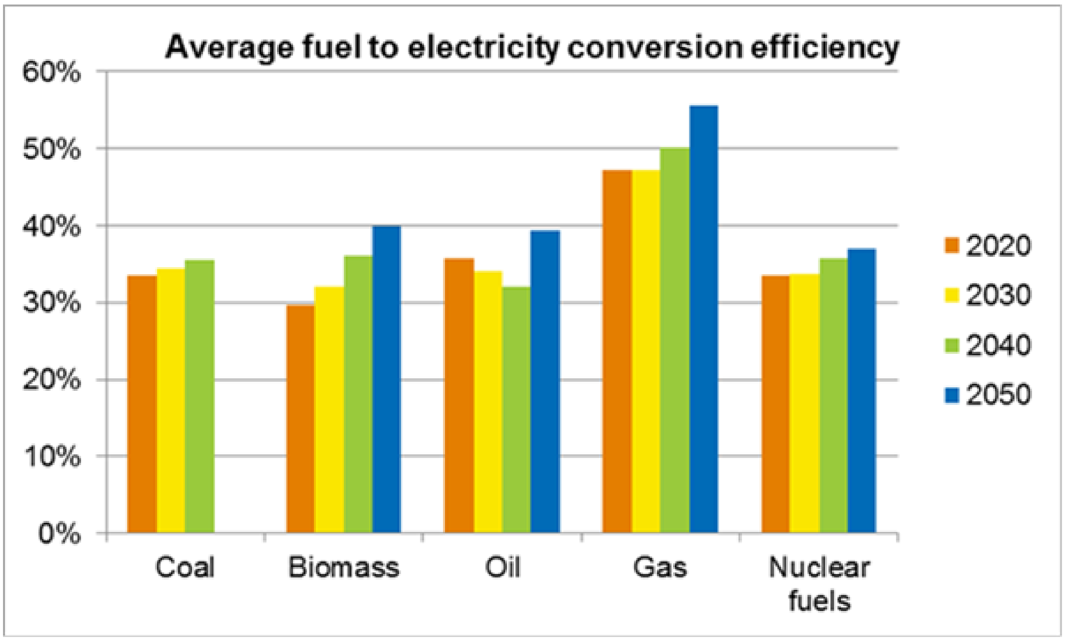
The following aspects are defined as foreground data in the sense of the Umberto model:

- Selection of the fuel mix:
  - In the case of this study the scenarios and cases described in Section 5 of the main report will be selected;
  - Within the Excel electricity module any member state situation or specific mixes can be calculated based on the corresponding setting of fuel/generation mix as given by the PRIMES data (also in combination also with accounting for country-specific generation efficiency and transmission and distribution losses);
  - The model allows the application of any further setting e.g. based on national or sector-specific statistics, Eurostat or IEA.
- Selection of technical level:

Each power plant module allows for the determination of the following technical parameters:

  - Electrical efficiency (fuel to electricity conversion efficiency): in the case of this study data provided by the EC based on the PRIMES model (see also Figure A55:).
  - Technical level of the emission reduction measures for fuel-fired power plants; the model allows the selection of three levels:
    - High level (corresponding to BAT): electrostatic dust precipitation or fabric filter; wet or semi-dry scrubber system, DENOX.
    - Medium level: electrostatic dust precipitation; dry scrubber, partly DENOX.
    - Low level: cyclone separator; partly dry scrubber, no DENOX.
  - The user is free to make any selection or to use a default setting for the current EU average: 50 % high level, 30 % medium level, 20 % low level.

Figure A55: Average fuel to electricity conversion efficiency; provided by the EC from the PRIMES model scenario 1.5TECH



Source: PRIMES; illustration: ifeu

A4.2.2.2 Coverage of LCI data for applied impact categories

The LCI data provided by the Umberto electricity model covers all the impact categories described in Section A3.9. Table A32: shows how the LCI data provided by the electricity model match with the proposed impact categories.

Table A32: Attribution of LCI data provided by the electricity model to the proposed impact categories

Impact category	Indicator and unit	Covered data category
Climate change	Greenhouse gas emissions GWP100 in CO_2 eq	CO_2 fossil, CH_4 fossil, CH_4biogenic, N_2O,…
Energy consumption	Cumulative energy demand in MJ (fossil and renewable)	• All fossil primary energy resources in MJ • Nuclear primary energy (by inversion of efficiency of nuclear power plant) • All renewable energy resources in MJ
Acidification	Acidification potential in SO_2 eq	SO_2, NO_x, NH_3, HCl, HF
Eutrophication	Eutrophication potential in PO_4^{3-} eq	NO_x, NH_3, (air) COD, nitrogen and phosphorous compounds (water)
Photochemical ozone formation	Photochemical Ozone Creation Potential POCP in NMVOC eq	$NMVOC_{total}$, CH_4
Ozone depletion	ODP in R11 eq	Diverse CFC from aluminium production (infrastructure)
Ionising radiation	Ionising radiation potentials in U235 eq	Numerous Radionuclides, measured in kilobecquerel (kBq)
Particulate matter	Particulate matter formation in PM2.5 eq	Primary particles (<2.5 µm), SO_2, NO_x, NH_3, NMVOC
Human toxicity, cancer and non-cancer	Comparative Toxic Unit for Human Health in CTUh	• Classical air pollutants (SO_2, NO_x, CO, fine particles, etc.) • Heavy metals (As, Sb, Cd, Hg, etc.) • Organic pollutants (PAH, PCB, dioxins, etc.)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems in CTUe	• COD, BOD5 • Sulphate and other salts • Heavy metals (As, Sb, Cd, Hg, etc.)
Resource depletion - Minerals and metals	ADP ultimate reserves in Sb eq	Fossil, mineral and metalliferous resources
Resource depletion - Energy Carriers	ADP fossil in MJ	All fossil primary energy resources in MJ
Land use	Land occupation in m^2 *a	Land occupation in m^2 *a
Water scarcity	Scarcity-adjusted water use in m^3	Fresh water

A4.3 Overall vehicle cycle

This Appendix subsection provides a summary of some of the key foreground data assumptions for the overall vehicle cycle that were used in the application of the LCA methodology to derive the results shown in the main report. Additional data/assumptions have also already been provided in the main report in Section 4.7.

A4.3.1 Vehicle specification

Table A33: Matrix summarising key sources and quality for vehicle specification

High	Medium	Low	N/A

Parameters	Cars	Vans	Rigid	Artic	Bus	Coach
Glider/trailer material composition	H/M (1, 2)	H (3)	H (3)	H (3)	H (3)	H (3)
Glider/trailer mass	H/M (1, 2)	H (3)	H (3)	H (3)	H (3)	H (3)
Component sizing	H/M (4)	H/M (4)	H/M (4)	H/M (4)	H/M (4)	H/M (4)
Component mass	H/M (5)	H/M (5)	H/M (5)	H/M (5)	H/M (5)	H/M (5)
Component material composition	Component material composition is based upon data from various sources, and was assumed similar for all vehicle types:					
xEV batteries	Material for batteries was based mainly on GREET (ANL, 2018), and study assumptions on the market mix of different battery types (H)					
Fuel cells and H_2 storage	Based on GREET (ANL, 2018) (H)					
Motors and power inverters	Based on datasets from (Nordelöf A. , Scalable IPMSM LCI Model v1.01.xlsm [Online]. Version 1.01, 2017), (Nordelöf A. , 2018) (H)					
HVAC heat-pump for xEVs	Ricardo analysis based on A2Mac1 databases (A2Mac1 Automotive Benchmarking, n.d.) (H).					
Other xEV components	Data for other xEV components was based on EMPA characterisations available in the Ecoinvent database (ecoinvent, 2018) (H)					
Exhaust aftertreatment	Based on datasets provided by Ricardo's technical experts (H).					
Other components (engine, transmission, exhaust, fuel tank, etc)	The material compositions for other components were mainly based on work that Ricardo has undertaken for the Low Carbon Vehicle Partnership (LowCVP) (Ricardo, 2018).					
Test-cycle (TC) energy consumption per km	H (6)	H (6)	H/M (7)	H/M (7)	H/M (7)	H/M (7)
Electric range	H (8)	H (8)	M (9)	M (9)	M (9)	M (9)
Battery Available SoC	H/M (10)	H/M (10)	M (12)	M (12)	M (12)	M (12)
Hybrid battery capacity	H (12)	H (12)	H/M (13)	H/M (13)	H/M (13)	H/M (13)

Sources:

#	Source	Quality	Comment
(1)	(ANL, 2018)	High	The overall composition of the vehicle/glider for LDVs (and the future scenarios for the change in this) is based on Ricardo analysis of lightweight vehicle data from GREET and future IEA scenarios for vehicle lightweighting.
(2)	(IEA, 2019)	High	
(3)	(Ricardo Energy & Environment et al., 2015)	High	Detailed analysis of lightweighting and the development of a MACC (marginal abatement cost-curve) model to assess cost-effectiveness, including mileage profiles and lifetimes for heavy duty vehicles. Key assumptions reviewed and tested with industry stakeholders.

#	Source	Quality	Comment
(4)	Ricardo analysis for this project – sizing.	High /Medium	Ricardo conducted an internal review with its engineering expert on previous assumptions for component sizing/scaling factors from (Ricardo Energy & Environment et al, 2016), (Ricardo Energy & Environment et al., 2015) and (Ricardo, 2018). These were then revised and expanded based on this review.
(5)	Ricardo analysis for this project – mass.	High /Medium	Component mass is determined based on the scaling factor methodology (Appendix Section A3.13.1) and Ricardo's assumptions on the potential changes in these over time (e.g. improvements to engine or motor power density in kW/kg), also informed by Automotive Council UK technology roadmaps. Certain components were assumed to have fixed mases.
(6)	(EEA, 2019), (EEA, 2019a), and (Ricardo Energy & Environment et al, 2016)	High	The performance (in MJ/km on the regulatory test-cycle) of alternative powertrains for LDVs, relative to the reference conventional ICEV powertrain, was mainly based on Ricardo and TU Graz's previous analysis for DG CLIMA. The performance of the LDV reference powertrains was based on DG JRC analysis of data from the provisional EEA CO_2 monitoring datasets for 2018, as outlined in the main report, Section 4.7.2.
(7)	Ricardo (2019)	High /Medium	The average energy consumption for reference ICEV-D powertrains was based on Ricardo simulation analysis using VECTO and (JRC, 2018) for artic lorries, as outlined in the main report, Section 4.7.2. The relative performance of gas-fuelled HDVs was based on Ricardo's experience with these technologies and a review of recent literature/analysis, e.g. (Cenex, 2019). No real-world data was available for the energy consumption profiles for certain alternative fuel powertrains (i.e. certain gas-fuelled vehicles, hybrids and xEVs). Ricardo carried out some simulation analysis using VECTO and additional post-processing of diesel ICEVs outputs to calculate hybrid and electric vehicle energy consumption profiles in relation to ICEVs. For (non-plug-in) hybrid electric vehicles, this assumed a parallel hybrid architecture for lorries and coaches (with a 30% 'degree of hybridisation' ratio), and a series-hybrid for urban busses.
(8)	Ricardo (2019)	High	Current typical xEV WLTP electric range assumptions for LDVs are based on a review of typical new models available on the EU market in 2019/2020.
(9)	(Ricardo Energy & Environment, 2019)	Medium	Assumptions for the electric range of actual and theoretical xEV heavy-duty vehicles was based on Ricardo's previous analysis for UK CCC, and a survey of current and forthcoming (/announced) models.
(10)	Ricardo assumptions for this project	High /Medium	Assumptions for battery available SoC from (Ricardo Energy & Environment et al, 2016), and new information on total/available battery capacity of new BEV models in 2019, were reviewed with Ricardo's battery experts. These were updated also based on anticipated future improvement in battery durability and power density. These latter parameters are the main limiting factors leading to the currently reserved/unavailable SoC shares for xEV batteries – i.e. sufficient power needs to be available to operate the vehicle within reasonable performance parameters at low battery charge status.
(11)	Ricardo assumptions for this project	Medium	For HDVs, a lower usable SoC is assumed than for LDVs as a safety margin, due to the need to maximise available power and to account for increased operational lifetime requirements/higher km over the life of the vehicle.
(12)	(Ricardo Energy & Environment et al, 2016)	High	Typical (non-plug-in) hybrid battery size for light-duty vehicles based on Ricardo's previous analysis, updated based on a recent market review.
(13)	Ricardo (2019)	High /Medium	Calculated based on the required battery capacity needed to store recuperated energy in Ricardo's high-level simulation analysis used to estimate hybrid heavy-duty vehicle performance – see earlier Source # (7).

Table A34: 2020 powertrain relative energy consumption assumptions by vehicle type, defined relative to the relevant reference powertrain (=100%)

Vehicle Type	Fuel No	ICEV-G	ICEV-D	ICEV-LPG	ICEV-CNG	ICEV-LNG	ICEV-CNGL	ICEV-LNGD	HEV-G	HEV-D	HEV-D-ERS	PHEV-G	PHEV-D	BEV	BEV-ERS	FCEV	FC-REEV
Car Lower Medium	Fuel1	**100%**	80%	100%	100%				80%	64%		80%	64%	26%		52%	52%
Car Large SUV	Fuel1	125%	**100%**	125%	125%				100%	80%		100%	80%	26%		52%	52%
Van N1 Class III	Fuel1	125%	**100%**	125%	125%				100%	80%		100%	80%	26%		52%	52%
Rigid Lorry 12t GVW Box	Fuel1		**100%**	110%	119%	119%	104%	103%		78%			78%	20%		40%	40%
Artic Lorry 40t GVW Box	Fuel1		**100%**			118%		103%		93%	93%		93%	40%	40%	80%	80%
Bus 12m SD	Fuel1		**100%**	110%	119%	119%	104%			60%			60%	20%	20%	40%	40%
Coach 24t GVW SD	Fuel1		**100%**		119%	119%	104%	103%		84%			84%	32%		64%	64%
Car Lower Medium	Fuel2											26%	26%				26%
Car Large SUV	Fuel2											26%	26%				26%
Van N1 Class III	Fuel2											26%	26%				26%
Rigid Lorry 12t GVW Box	Fuel2							100%					20%				20%
Artic Lorry 40t GVW Box	Fuel2							100%			39%		40%		39%		40%
Bus 12m SD	Fuel2												20%		20%		20%
Coach 24t GVW SD	Fuel2							100%					32%				32%

Notes: This table contains the assumed average energy consumption for Cycle1 compared to the Reference Powertrain (in **bold text, highlighted cells**). This EXCLUDES charging losses, which are added later in the calculations. G = Gasoline, D = Diesel. For Fuel 1: for PHEV / REEV / ERS, this is the efficiency operating on primary liquid/gaseous fuel (e.g. for PHEV-G, Fuel1 = Gasoline, Fuel2 = Electricity). For -ERS powertrains, Fuel2 is electricity from an overhead catenary (so for BEV-ERS, Fuel1 is electricity from the on-board battery instead).

Figure A56: Summary of the vehicle mass by system for the reference powertrain type

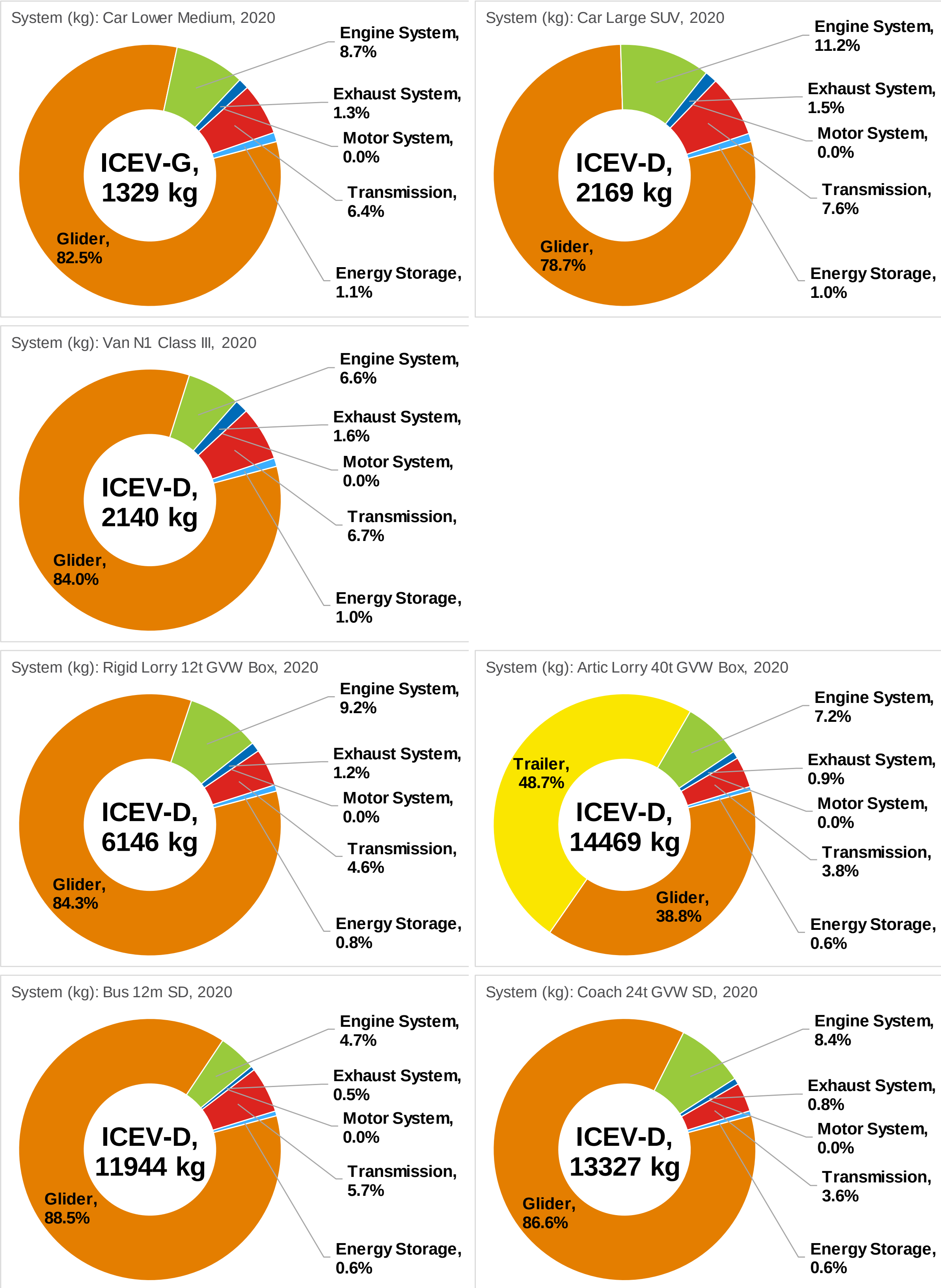
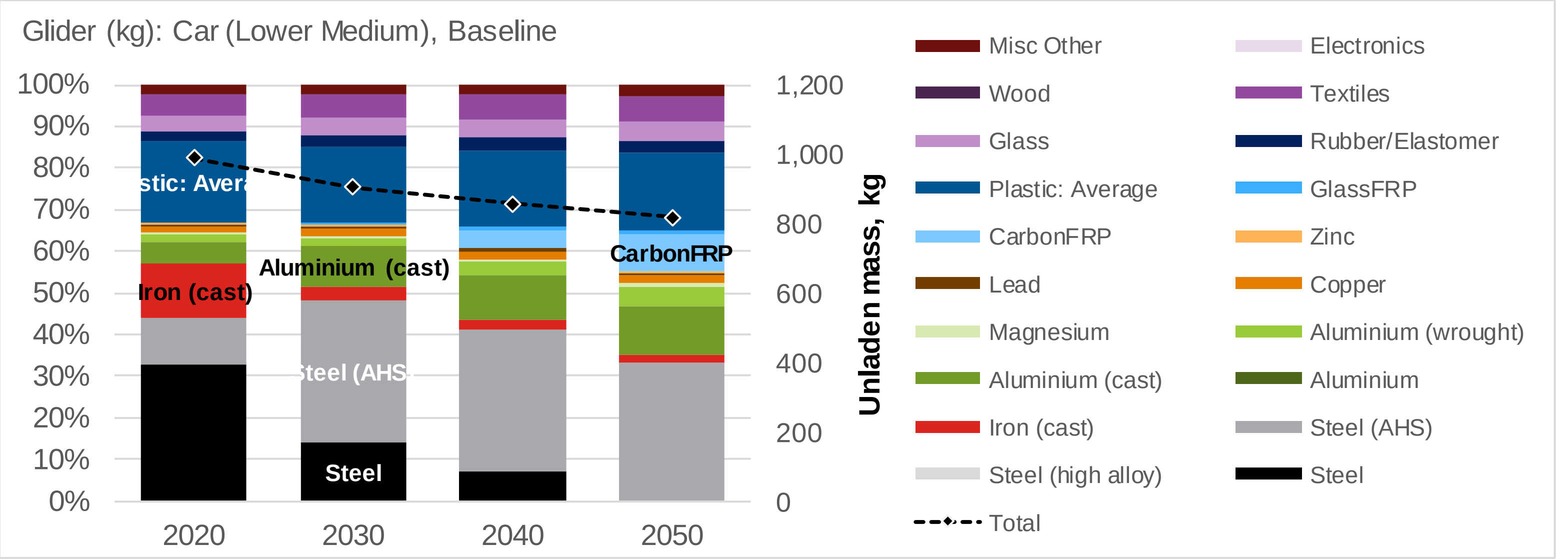


Figure A57: Summary of the baseline vehicle glider mass and composition assumptions

Lower Medium Car



Large SUV Car

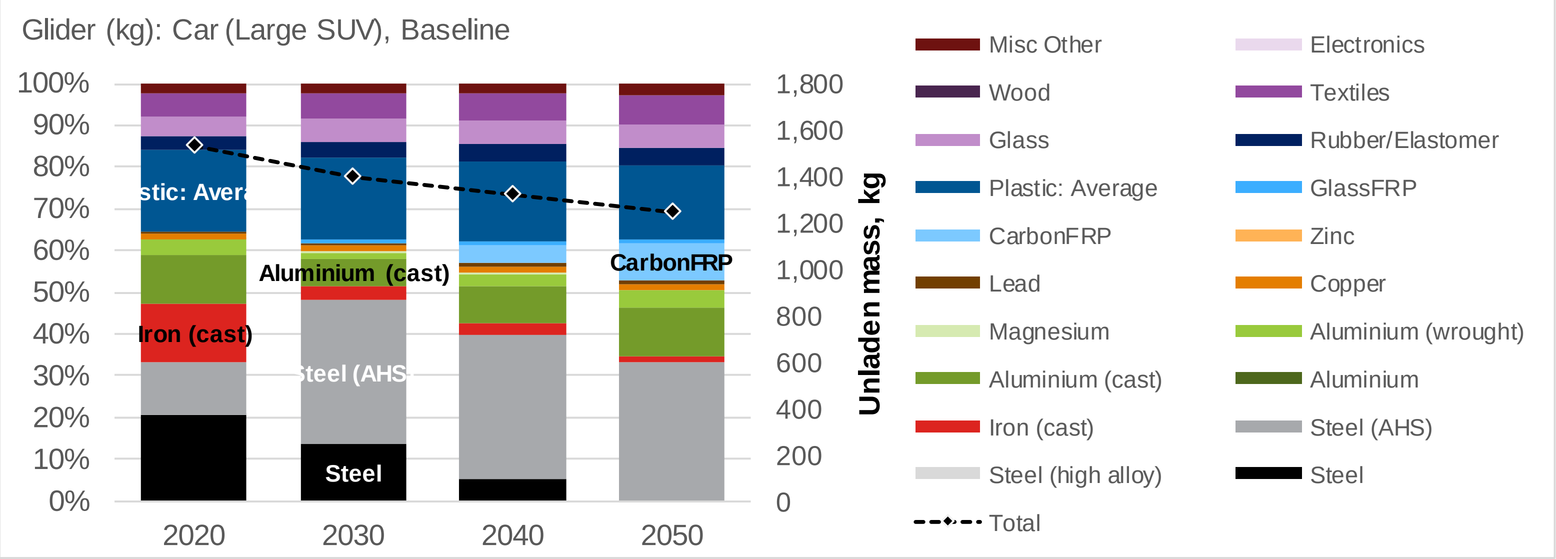
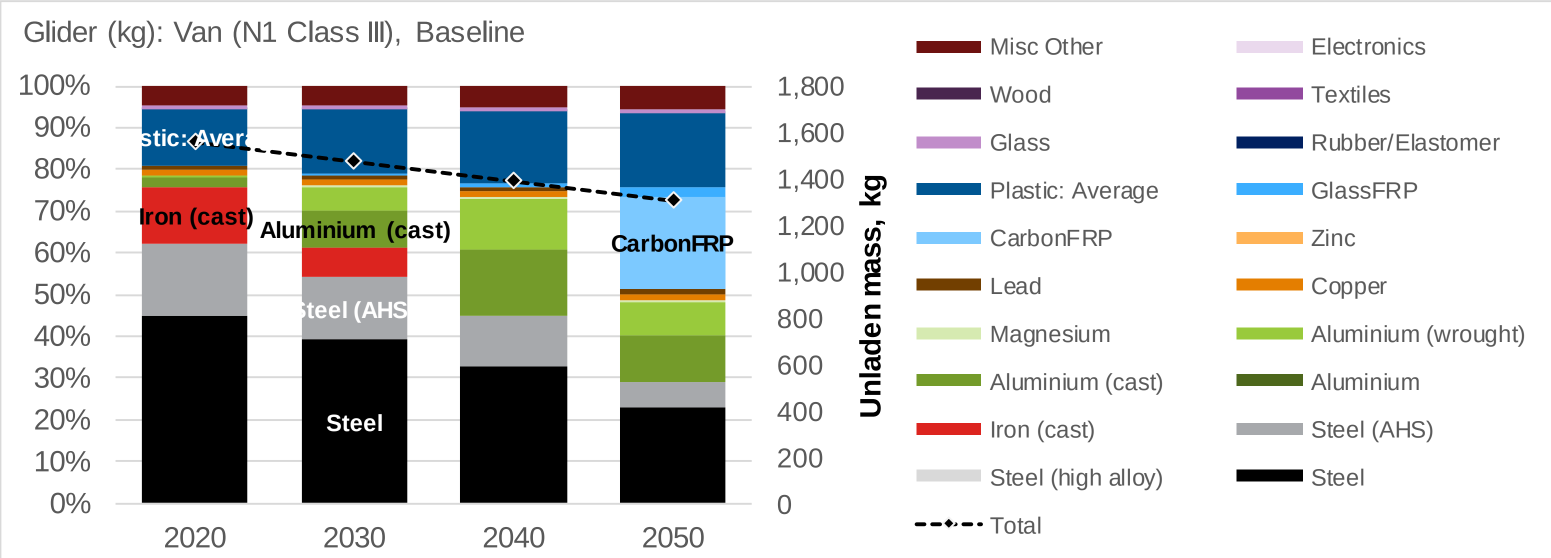


Figure A57: Summary of the baseline vehicle glider mass and composition assumptions

N1 Class III Van (3.5t)



12t GVW Rigid Lorry

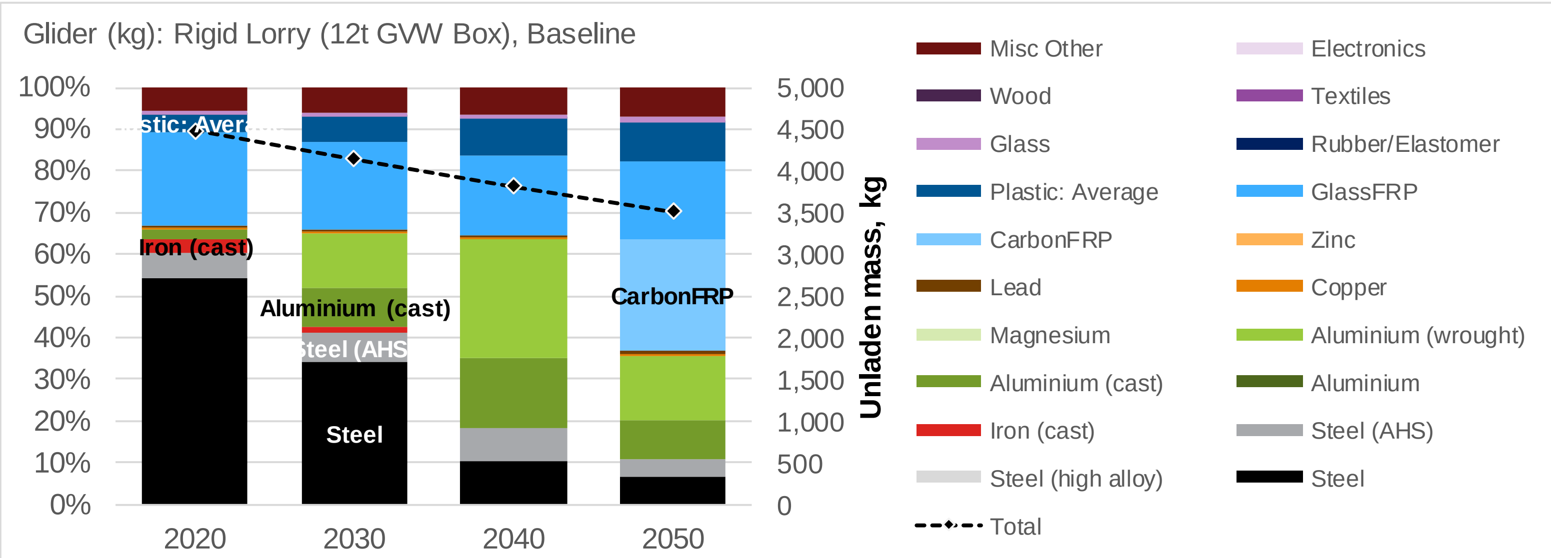
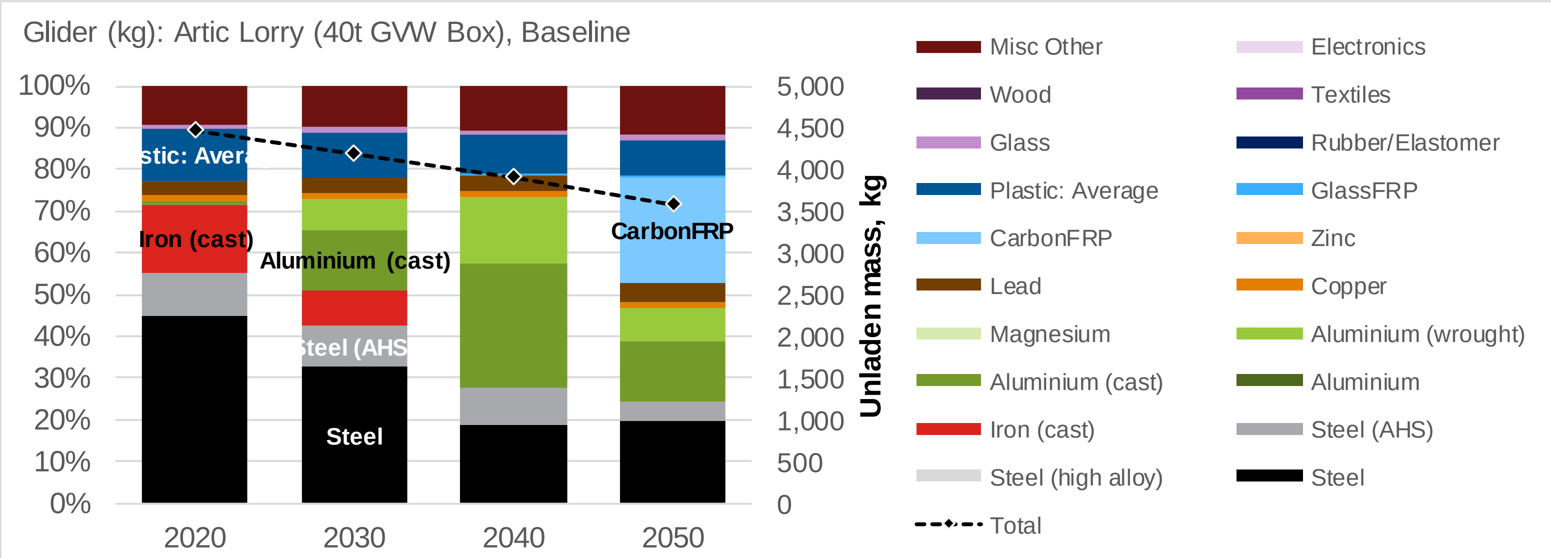


Figure A57: Summary of the baseline vehicle glider mass and composition assumptions

40t GVW Artic Lorry



12m Single Deck Bus

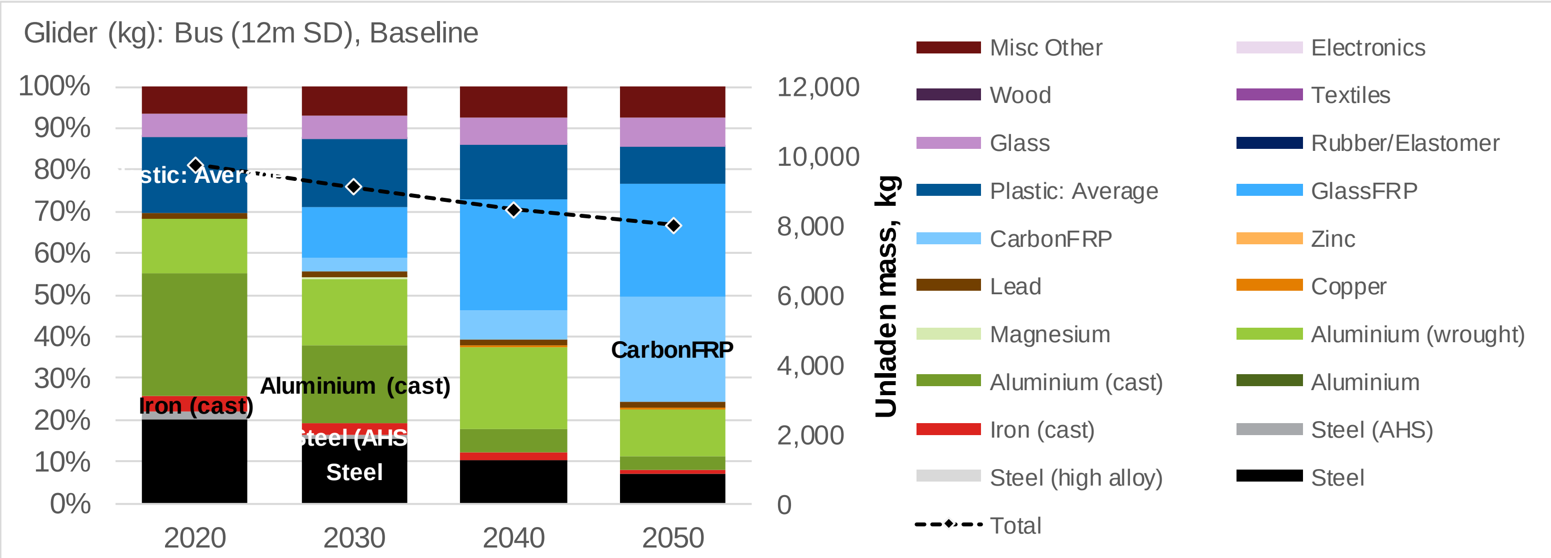
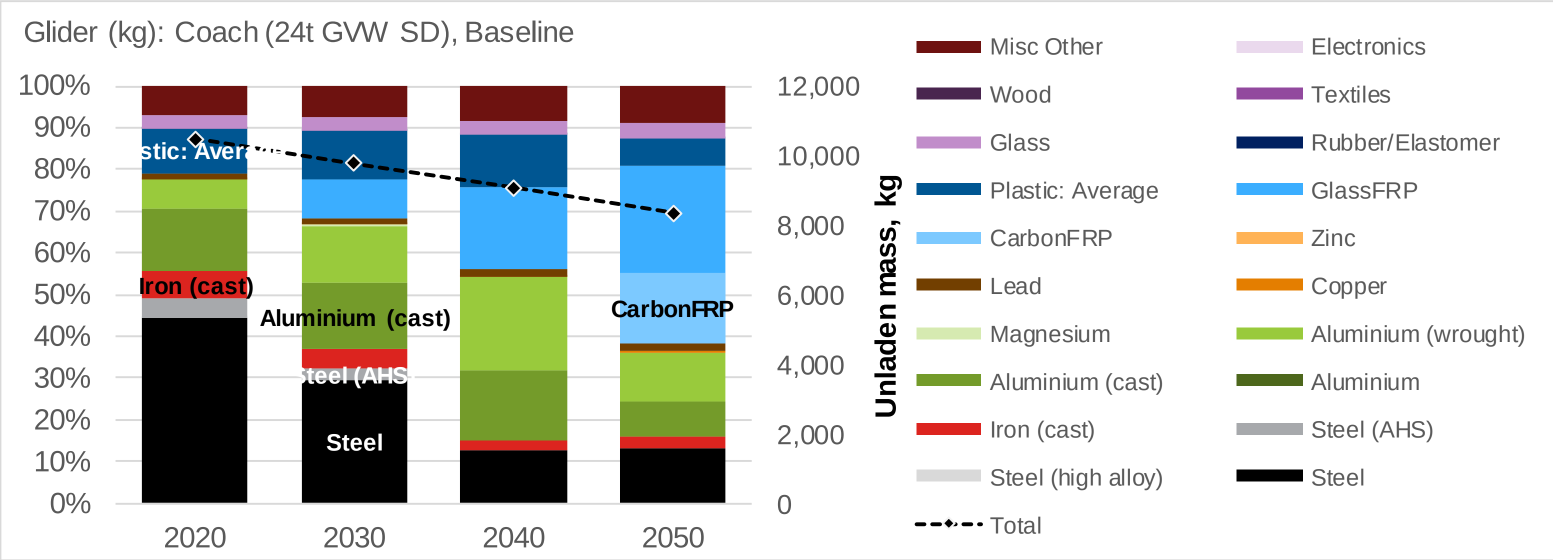


Figure A57: Summary of the baseline vehicle glider mass and composition assumptions

24t GVW SD Coach



Source: Ricardo analysis for this study.

Table A35: Assumed battery and FC performance parameters for xEVs

Component	Parameter	Unit	2020	2030	2040	2050
Fuel Cell System	Power Density	kW/kg	1.022	1.471	2.119	3.051
Fuel Cell	*Power Density*	*kW/kg*	*2.089*	*3.009*	*4.332*	*6.239*
Fuel Cell Periphery	*Power Density*	*kW/kg*	*2.000*	*2.880*	*4.147*	*5.972*
Fuel Cell System	Life	Hours	5,000	8,000	9,000	10,000
Battery	Cycle Life	#Cycles	2,000	3,000	5,000	6,000

Table A36: Electric range assumptions for xEVs by vehicle and powertrain type, default regulatory cycle*

	Powertrain	Sensitivity	Unit	2020	2030	2040	2050
Car Lower Medium	PHEV-G	Default	km	50	60	60	60
Car Large SUV	PHEV-G	Default	km	50	60	60	60
Van N1 Class III	PHEV-G	Default	km	50	60	60	60
Car Lower Medium	PHEV-D	Default	km	50	60	60	60
Car Large SUV	PHEV-D	Default	km	50	60	60	60
Van N1 Class III	PHEV-D	Default	km	50	60	60	60
Rigid Lorry 12t GVW Box	PHEV-D	Default	km	35	70	70	70
Artic Lorry 40t GVW Box	PHEV-D	Default	km	80	100	100	100
Bus 12m SD	PHEV-D	Default	km	50	100	100	100
Coach 24t GVW SD	PHEV-D	Default	km	30	60	60	60
Car Lower Medium	BEV	Default	km	300	460	540	600
Car Large SUV	BEV	Default	km	480	640	720	720
Van N1 Class III	BEV	Default	km	170	290	400	400
Rigid Lorry 12t GVW Box	BEV	Default	km	200	300	350	350
Artic Lorry 40t GVW Box	BEV	Default	km	500	1100	1500	1500
Bus 12m SD	BEV	Default	km	250	350	400	400
Coach 24t GVW SD	BEV	Default	km	300	400	500	600
Artic Lorry 40t GVW Box	BEV-ERS	Default	km	250	270	290	300
Bus 12m SD	BEV-ERS	Default	km	80	120	120	120
Car Lower Medium	FCEV	Default	km	5	5	5	5
Car Large SUV	FCEV	Default	km	5	5	5	5
Van N1 Class III	FCEV	Default	km	5	5	5	5
Rigid Lorry 12t GVW Box	FCEV	Default	km	5	5	5	5
Artic Lorry 40t GVW Box	FCEV	Default	km	5	5	5	5
Bus 12m SD	FCEV	Default	km	5	5	5	5
Coach 24t GVW SD	FCEV	Default	km	5	5	5	5
Rigid Lorry 12t GVW Box	FC-REEV	Default	km	100	100	100	100

	Powertrain	Sensitivity	Unit	2020	2030	2040	2050
Artic Lorry 40t GVW Box	FC-REEV	Default	km	150	150	150	150
Bus 12m SD	FC-REEV	Default	km	50	100	100	100
Coach 24t GVW SD	FC-REEV	Default	km	60	100	100	100
Car Lower Medium	PHEV-G	Low	km	40	50	50	50
Car Large SUV	PHEV-G	Low	km	40	50	50	50
Van N1 Class III	PHEV-G	Low	km	40	50	50	50
Car Lower Medium	PHEV-D	Low	km	40	50	50	50
Car Large SUV	PHEV-D	Low	km	40	50	50	50
Van N1 Class III	PHEV-D	Low	km	40	50	50	50
Rigid Lorry 12t GVW Box	PHEV-D	Low	km	28	56	56	56
Artic Lorry 40t GVW Box	PHEV-D	Low	km	64	80	80	80
Bus 12m SD	PHEV-D	Low	km	40	80	80	80
Coach 24t GVW SD	PHEV-D	Low	km	24	48	48	48
Car Lower Medium	BEV	Low	km	250	400	460	500
Car Large SUV	BEV	Low	km	430	575	650	650
Van N1 Class III	BEV	Low	km	155	260	360	360
Rigid Lorry 12t GVW Box	BEV	Low	km	160	240	280	280
Artic Lorry 40t GVW Box	BEV	Low	km	400	880	1200	1200
Bus 12m SD	BEV	Low	km	200	280	320	320
Coach 24t GVW SD	BEV	Low	km	240	320	400	480
Artic Lorry 40t GVW Box	BEV-ERS	Low	km	200	216	232	240
Bus 12m SD	BEV-ERS	Low	km	64	96	96	96
Car Lower Medium	FCEV	Low	km	5	5	5	5
Car Large SUV	FCEV	Low	km	5	5	5	5
Van N1 Class III	FCEV	Low	km	5	5	5	5
Rigid Lorry 12t GVW Box	FCEV	Low	km	5	5	5	5
Artic Lorry 40t GVW Box	FCEV	Low	km	5	5	5	5
Bus 12m SD	FCEV	Low	km	5	5	5	5
Coach 24t GVW SD	FCEV	Low	km	5	5	5	5
Rigid Lorry 12t GVW Box	FC-REEV	Low	km	80	80	80	80
Artic Lorry 40t GVW Box	FC-REEV	Low	km	120	120	120	120
Bus 12m SD	FC-REEV	Low	km	40	80	80	80
Coach 24t GVW SD	FC-REEV	Low	km	48	80	80	80
Car Lower Medium	PHEV-G	High	km	60	70	70	70
Car Large SUV	PHEV-G	High	km	60	70	70	70
Van N1 Class III	PHEV-G	High	km	60	70	70	70
Car Lower Medium	PHEV-D	High	km	60	70	70	70
Car Large SUV	PHEV-D	High	km	60	70	70	70

	Powertrain	Sensitivity	Unit	2020	2030	2040	2050
Van N1 Class III	PHEV-D	High	km	60	70	70	70
Rigid Lorry 12t GVW Box	PHEV-D	High	km	42	84	84	84
Artic Lorry 40t GVW Box	PHEV-D	High	km	96	120	120	120
Bus 12m SD	PHEV-D	High	km	60	120	120	120
Coach 24t GVW SD	PHEV-D	High	km	36	72	72	72
Car Lower Medium	BEV	High	km	350	500	600	700
Car Large SUV	BEV	High	km	530	705	790	790
Van N1 Class III	BEV	High	km	185	320	440	440
Rigid Lorry 12t GVW Box	BEV	High	km	240	360	420	420
Artic Lorry 40t GVW Box	BEV	High	km	600	1320	1800	1800
Bus 12m SD	BEV	High	km	300	420	480	480
Coach 24t GVW SD	BEV	High	km	360	480	600	720
Artic Lorry 40t GVW Box	BEV-ERS	High	km	300	324	348	360
Bus 12m SD	BEV-ERS	High	km	96	144	144	144
Car Lower Medium	FCEV	High	km	5	5	5	5
Car Large SUV	FCEV	High	km	5	5	5	5
Van N1 Class III	FCEV	High	km	5	5	5	5
Rigid Lorry 12t GVW Box	FCEV	High	km	5	5	5	5
Artic Lorry 40t GVW Box	FCEV	High	km	5	5	5	5
Bus 12m SD	FCEV	High	km	5	5	5	5
Coach 24t GVW SD	FCEV	High	km	5	5	5	5
Rigid Lorry 12t GVW Box	FC-REEV	High	km	120	120	120	120
Artic Lorry 40t GVW Box	FC-REEV	High	km	180	180	180	180
Bus 12m SD	FC-REEV	High	km	60	120	120	120
Coach 24t GVW SD	FC-REEV	High	km	72	120	120	120

Notes: * For cars and vans the default regulatory cycle is WLTP; for HDVs the regulatory cycles are based on those used in vehicle certification as defined in the VECTO simulation tool: for rigid lorries it is the ‘Urban Delivery’ cycle, for artic lorries it is ‘Long-Haul’ cycle, for buses it is ‘Urban Bus’ cycle, and for coaches it is ‘Coach’ cycle.

For PHEVs and REEVs, a real-world electric range is also subsequently calculated in the vehicle LCA modelling (which depends on relevant uplifts and adjustments outlined in Appendix Section A3.13.3), which is then used to determine the operational share running on electricity for these vehicles.

Table A37: Battery usable SoC assumptions for xEVs by vehicle and powertrain type

Powertrain	Unit	Assumptions on LDV xEV battery available SoC				HDVs*
		2020	2030	2040	2050	All periods
HEV-G	%	50%	50%	50%	50%	N/A
HEV-D	%	50%	50%	50%	50%	-0%
HEV-D-ERS	%	50%	50%	50%	50%	-0%
PHEV-G	%	75%	90%	95%	95%	N/A
PHEV-D	%	75%	90%	95%	95%	-5%
REEV-G	%	80%	90%	95%	95%	N/A
REEV-D	%	80%	90%	95%	95%	-5%
BEV	%	90%	95%	95%	95%	-10%
BEV-ERS**	%	90%	95%	95%	95%	-5%
FCEV	%	50%	50%	50%	50%	-5%
FC-REEV	%	80%	90%	95%	95%	-5%

Notes: *For HDVs, a lower usable SoC is assumed than for LDVs as a safety margin, due to the need to maximise available power and to account for increased operational lifetime requirements/higher km over the life of the vehicle. **Only available for HDV applications.

Table A38: Hybrid battery capacity (in kWh) for HEVs by vehicle and powertrain type

Vehicle Type	Powertrain	Unit	All Periods
Car Lower Medium	HEV-G	kWh	1.5
Car Large SUV	HEV-G	kWh	2.5
Van N1 Class III	HEV-G	kWh	2
Car Lower Medium	HEV-D	kWh	1.5
Car Large SUV	HEV-D	kWh	2.5
Van N1 Class III	HEV-D	kWh	2
Rigid Lorry 12t GVW Box	HEV-D	kWh	5
Artic Lorry 40t GVW Box	HEV-D	kWh	10
Bus 12m SD	HEV-D	kWh	30
Coach 24t GVW SD	HEV-D	kWh	10
Rigid Lorry 12t GVW Box	HEV-D-ERS	kWh	5
Artic Lorry 40t GVW Box	HEV-D-ERS	kWh	10
Bus 12m SD	HEV-D-ERS	kWh	30
Coach 24t GVW SD	HEV-D-ERS	kWh	10

Note: Hybrid vehicles are assumed to have a fixed energy storage capacity. Assumptions are based on values for typical available models, or estimates based on Ricardo simulation analysis where these are absent (for HDVs).

A4.3.2 Vehicle manufacturing

Table A39: Matrix summarising key sources and quality for vehicle manufacturing calculations

High	Medium	Low	N/A

Parameters	Source(s)	Quality
PEF CFF parameters	PEF default values were used for the available materials and according to the guidance on the application of the PEF CFF (circular footprint formula) (JRC, 2018a). For the remaining materials Ricardo assigned appropriate values based on the PEF defaults. These were used to determine the impacts of utilised materials in manufacturing in combination with the impact factors for primary/virgin and secondary/recycled materials using the first part of the PEF CFF (see Figure A43) for material.	M
Recycled content (R1)	PEF default values were used for the available materials, from (JRC, 2018a), supplemented by values from Ricardo's previous analyses in this area (Ricardo, 2018) and (Ricardo Energy & Environment, 2019).	M
Material impacts	Material impacts were based on the datasets from background LCI databases (see Section A4.1), with future impacts estimated based on electricity decarbonisation scenarios – as outlined in the methodology Appendix Section A3.13.2.1.	H/M
Manufacturing material loss factors	Manufacturing material loss factors were only available for Steel and Aluminium (taken from (IEA, 2019)) and for battery materials (taken from GREET, (ANL, 2018)). Other manufacturing material losses were assumed to be zero; this assumption was assessed to be highly unlikely to significantly affect the comparison between different powertrains.	H/L
Material use	Material use was based on combination of the derived component material composition and mass and the material loss factors.	H
Manufacturing energy consumption	Data from GREET (ANL, 2018) was used for the energy consumption for vehicle manufacturing/assembly (with battery manufacturing accounted for separately).	H
Regional vehicle manufacturing mix	Based on ACEA/OICA vehicle production statistics, data from ACEA's Pocket Guide, and Eurostat data on imports – see Figure A58.	H
Vehicle manufacturing electricity impacts	Calculated based on a weighted average of the % shares of vehicle manufacturing in different regions with the electricity impacts for the different countries/regions.	H
Vehicle manufacturing non-energy impacts	Data from GREET (ANL, 2018) was used for the non-energy consumption impacts from vehicle manufacturing/assembly.	H
Battery manufacturing	Battery manufacturing (including material use, energy consumption and other impacts) were defined using a dedicated manufacturing module and were mostly based on GREET. Further information is provided in Section A4.3.2.1 on this.	H

Table A40: PEF Circular Footprint Formula parameters used in the analysis by material

Material	Category	CatNo	Units	A	B	Qsin/Qp	Qsout/Qp	Xer	LHV
Ferrite	SteelIron	100	Factor	0.2	0	1	1	25%	0.0
Iron	SteelIron	100	Factor	0.2	0	1	1	25%	0.0

Material	Category	CatNo	Units	A	B	Qsin/Qp	Qsout/Qp	Xer	LHV
Iron (cast)	SteelIron	100	Factor	0.2	0	1	1	25%	1.0
Steel	SteelIron	100	Factor	0.2	0	1	1	25%	2.0
Steel (unalloyed)	SteelIron	100	Factor	0.2	0	1	1	25%	0.0
Steel (low alloy)	SteelIron	100	Factor	0.2	0	1	1	25%	0.0
Steel (high alloy)	SteelIron	100	Factor	0.2	0	1	1	25%	0.0
Steel (AHS)	SteelIron	100	Factor	0.2	0	1	1	25%	0.0
Aluminium	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Aluminium (cast)	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Aluminium (wrought)	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Lithium	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Magnesium	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Titanium	LightMet	200	Factor	0.2	0	1	1	25%	0.0
Brass	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Cobalt	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Copper	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Lead	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Manganese	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Nickel	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Zinc	HeavyMet	300	Factor	0.2	0	1	1	25%	0.0
Gold	SpecialMet	400	Factor	0.2	0	1	1	25%	0.0
Palladium	SpecialMet	400	Factor	0.2	0	1	1	25%	0.0
Platinum	SpecialMet	400	Factor	0.2	0	1	1	25%	0.0
Rhodium	SpecialMet	400	Factor	0.2	0	1	1	25%	0.0
CarbonFRP	PlasticPol	500	Factor	0.2	0	0.75	0.75	25%	24.9
CarbonFRP (HPV)	PlasticPol	500	Factor	0.2	0	0.75	0.75	25%	24.9
GlassFRP	PlasticPol	500	Factor	0.2	0	0.75	0.75	25%	24.9
Binder: PTFE	OtherSub	800	Factor	0.5	0	0.75	0.75	25%	24.9
Plastic: Average	PlasticPol	500	Factor	0.5	0	0.75	0.75	25%	24.9
Plastic: PE	PlasticPol	500	Factor	0.5	0	0.9	0.9	25%	24.9
Plastic: PP	PlasticPol	500	Factor	0.5	0	0.9	0.9	25%	24.9
Resin: Average	PlasticPol	500	Factor	0.2	0	0.75	0.75	25%	24.9
Rubber/Elastomer	PlasticPol	500	Factor	0.5	0	0.75	0.75	25%	24.9
Silicone Product	PlasticPol	500	Factor	0.2	0	0.75	0.75	25%	24.9
AdBlue	Fluids	600	Factor	0.2	0	1	1	25%	0.0
Coolant: Ethylene Glycol	Fluids	600	Factor	0.2	0	0.9	0.9	25%	0.0
Coolant: Propylene Glycol	Fluids	600	Factor	0.2	0	0.9	0.9	25%	0.0
Lubricating Oil	Fluids	600	Factor	0.2	0	0.75	0.75	25%	14.1

Material	Category	CatNo	Units	A	B	Qsin/Qp	Qsout/Qp	Xer	LHV
Screenwash	Fluids	600	Factor	0.2	0	0.75	0.75	25%	0.0
Water	Fluids	600	Factor	0.2	0	1	1	25%	0.0
Other fluids	Fluids	600	Factor	0.2	0	0.75	0.75	25%	24.9
Cordierite	OtherMat	700	Factor	0.2	0	1	1	25%	0.0
Glass	OtherMat	700	Factor	0.2	0	1	1	25%	0.0
Nd(Dy)FeB	OtherMat	700	Factor	0.2	0	1	1	25%	0.0
Textiles	OtherMat	700	Factor	0.8	0	0.75	0.75	25%	14.3
Thermal Insulation	OtherMat	700	Factor	0.5	0	0.9	0.9	25%	24.9
Wood	OtherMat	700	Factor	0.8	0	0.75	0.75	25%	16.8
Aluminium Sulphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Ammonia	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Ammonium Hydroxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Carbon Paper	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	32.8
Cobalt Sulphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Diammonium Phosphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Electrolyte: Dimethyl Carbonate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Electrolyte: Ethylene Carbonate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Graphite/Carbon	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	32.8
Hydrochloric Acid	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Hydrogen Peroxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Iron Oxide (Fe3O4)	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Iron Sulphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
LiPF6	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
LiPON	OtherSub	800	Factor	**0.2**	**0**	**0.9**	**0.9**	25%	0.0
Lime (CaO)	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Lithium Carbonate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Lithium Hydroxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Magnesium Hydroxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Manganese Oxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Manganese Sulphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
NaPF6	OtherSub	800	Factor	**0.2**	**0**	**0.9**	**0.9**	25%	0.0
Nickel Sulphate	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
NMP	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Oxygen	OtherSub	800	Factor	0.2	0	1	1	25%	0.0
Phosphoric Acid	OtherSub	800	Factor	0.2	0	1	1	25%	0.0
Phosphorus	OtherSub	800	Factor	0.2	0	1	1	25%	0.0

Material	Category	CatNo	Units	A	B	Qsin/Qp	Qsout/Qp	Xer	LHV
Silicon	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Sodium	OtherSub	800	Factor	0.2	0	1	1	25%	0.0
Sodium Hydroxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Sulphuric Acid	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Titanium Dioxide	OtherSub	800	Factor	0.2	0	0.9	0.9	25%	0.0
Vanadium	OtherSub	800	Factor	0.2	0	1	1	25%	0.0
Vanadium Oxide	OtherSub	800	Factor	0.2	0	1	1	25%	0.0
Misc Other	OtherSub	800	Factor	0.5	0	0.5	0.5	25%	0.0
Electronics	Subcomp	2000	Factor	0.2	0	0.75	0.75	25%	0.0

Source: Ricardo, based on default data provided in (JRC, 2018a) and alongside (RECHARGE, 2018).

Table A41: Vehicle manufacturing and EoL: Recycled content, recycling rate and material loss factor assumptions by material (Default, EUSVC)

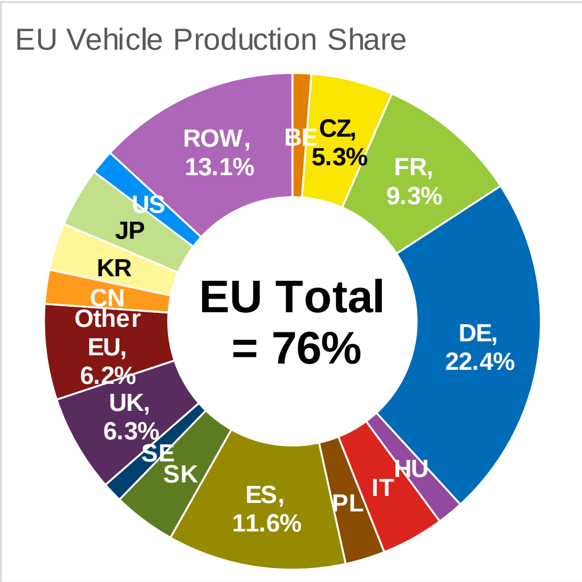
	Use Factor*	Recy'd Content, R1	Recycling Recovery, R2					
	Default	Default	Default	EU SVC Sensitivity**				
Material	2020	2020	2020	2020	2025	2030	2035	2040-
Ferrite	100%	0%	85%	85%	85%	85%	85%	85%
Iron (cast)	133%	54%	85%	85%	85%	85%	85%	85%
Steel	133%	54%	85%	85%	85%	85%	85%	85%
Steel (unalloyed)	133%	54%	95%	95%	95%	95%	95%	95%
Steel (low alloy)	133%	54%	95%	95%	95%	95%	95%	95%
Steel (high alloy)	133%	54%	95%	95%	95%	95%	95%	95%
Steel (AHS)	133%	54%	95%	95%	95%	95%	95%	95%
Aluminium	119%	33%	91%	95%	95%	95%	95%	95%
Aluminium (cast)	119%	33%	91%	95%	95%	95%	95%	95%
Aluminium (wrought)	119%	33%	91%	95%	95%	95%	95%	95%
Magnesium	100%	50%	100%	100%	100%	100%	100%	100%
Titanium	100%	54%	54%	54%	54%	54%	54%	54%
Brass	100%	0%	80%	80%	80%	80%	80%	80%
Copper	100%	72%	80%	80%	80%	80%	80%	80%
Lead	100%	62%	100%	100%	100%	100%	100%	100%
Nickel	100%	0%	95%	95%	95%	95%	95%	95%
Zinc	100%	30%	90%	90%	90%	90%	90%	90%
Gold	100%	0%	95%	95%	95%	95%	95%	95%
Palladium	100%	0%	95%	95%	95%	95%	95%	95%
Platinum	100%	0%	95%	95%	95%	95%	95%	95%
Rhodium	100%	0%	95%	95%	95%	95%	95%	95%
CarbonFRP	100%	10%	10%	10%	20%	30%	40%	50%

	Use Factor*	Recy'd Content, R1	Recycling Recovery, R2					
	Default	Default	Default	EU SVC Sensitivity**				
Material	2020	2020	2020	2020	2025	2030	2035	2040-
CarbonFRP (HPV)	100%	0%	10%	10%	20%	30%	40%	50%
GlassFRP	100%	0%	10%	10%	20%	30%	40%	50%
Plastic: Average	100%	24%	93%	93%	40%	50%	50%	50%
Plastic: PE	100%	24%	93%	93%	40%	50%	50%	50%
Plastic: PP	100%	24%	93%	93%	30%	40%	50%	50%
Resin: Average	100%	24%	85%	85%	30%	40%	50%	50%
Rubber/Elastomer	100%	0%	85%	85%	85%	85%	85%	85%
Silicone Product	100%	0%	85%	85%	85%	85%	85%	85%
AdBlue	100%	0%	90%	90%	90%	90%	90%	90%
Coolant: Ethylene Glycol	100%	0%	90%	90%	90%	90%	90%	90%
Lubricating Oil	100%	0%	98%	98%	98%	98%	98%	98%
Screenwash	100%	0%		0%	0%	0%	0%	0%
Water	100%	0%		0%	0%	0%	0%	0%
Other fluids	100%	100%	50%	50%	50%	50%	50%	50%
Cordierite	100%	0%		0%	0%	0%	0%	0%
Glass	100%	0%	60%	60%	60%	60%	60%	60%
Nd(Dy)FeB	100%	0%		80%	80%	80%	80%	80%
Textiles	100%	0%	80%	80%	80%	80%	80%	80%
Thermal Insulation	100%	0%		0%	0%	0%	0%	0%
Wood	100%	0%	38%	38%	38%	38%	38%	38%
Carbon Paper	100%	0%		0%	0%	0%	0%	0%
Graphite/Carbon	100%	0%		0%	0%	0%	0%	0%
Silicon	100%	0%		0%	0%	0%	0%	0%
Misc Other	100%	0%		0%	0%	0%	0%	0%
Electronics	100%	0%	50%	50%	50%	50%	50%	50%
Battery	100%	0%	95%	95%	95%	95%	95%	95%

Notes: * The 'Use Factor' is defined as the proportion of material used in manufacturing as a percentage of the content in the finished component/vehicle – i.e. values are greater than 100% where losses are assumed. In the SVC** sensitivity, by 2030 the material use in vehicle/component manufacturing for steel is assumed to reduce to 114% of the vehicle content, and for aluminium it is reduced to 105% of the vehicle content. ** SVC = Sustainable Value Chain sensitivity.

Source: Recycled content and recycling rates based on PEF Defaults (JRC, 2018a), and previous analysis by Ricardo in (Ricardo, 2018) and (Ricardo Energy & Environment, 2019). Assumptions for material losses based on (IEA, 2019).

Figure A58: Scenario assumptions for regional vehicle manufacturing



Notes: Used to determine the average electricity impacts from electricity used in vehicle assembly.
Source: Based on statistics from ACEA for EU manufacturing, and Eurostat for vehicle imports.

A4.3.2.1 Battery manufacturing

The GREET 2018 update LCA model produced by the Argonne National Laboratory (ANL, 2018) was used as the primary source for most of the input data/the methodological approach for the application of battery manufacturing and recycling calculations.

The energy consumption in battery manufacturing accounts for a significant component of the overall impacts. Two key data sources for the energy demand in the battery manufacturing stage have been used. Reports by the Argonne National Laboratory that feed into the GREET model include estimations of energy consumption in the battery and cell assembly stage (Dunn. JB., 2012) and cathode material formation stage (Dai Q. K., 2018). The manufacturing process is generally very similar for different lithium-ion battery chemistries (though more differences are likely for some future battery types, e.g. solid-state battery chemistries), so no significant differences are anticipated. Energy consumption data is also provided in default datasets provided alongside the PEFCR for rechargeable batteries (RECHARGE, 2018), however in this case only aggregated data for an assumed 100% energy consumption of electricity is provided/assumed. Data from these two different sources is provided in Table A42 below. The largest portion of energy consumption is to provide heat or dry room conditions. In reality, different manufacturing facilities use different sources of energy for this heat, with some using natural gas (or other fossil fuels) and others using electricity. There was no information on the typical market split between these different options. Therefore a default energy input representing a midpoint between these two sources has been calculated. Within this calculation for the 'Default', the PEFCR electricity value (41.2) for cell formation has been shared between the 'Cell' and (missing) 'Cathode' stage assuming a similar distribution as for natural gas from GREET.

Table A42: Energy for manufacturing of pack, cell and cathode.

Battery Area	Type	Unit	GREET	PEFCR	Default
Periphery	Electricity	MJ/kg battery	0.001	0.001	0.001
Cell	Electricity	MJ/kg battery	4.275	41.200	11.635
Cell	Natural Gas	MJ/kg battery	20.015	N/A	10.008
Cathode	Electricity	MJ/kg battery	5.040	N/A	13.622
Cathode	Natural Gas	MJ/kg battery	23.355	N/A	11.677

Future improvements in energy consumption in battery manufacturing, as a result of efficiencies in the industrial process, have been accounted for via a percentage factor (Table A43). These improvement values are based on the assumption that production facilities will move towards the energy use that we see in 'Gigafactory' scale facilities (Kurland, 2019). No improvement is considered beyond 2040 and a 55% decrease in energy use relative to 2020.

Table A43: Battery manufacturing energy consumption improvement

Battery Area	Type	Unit	2020	2025	2030	2035	2040	2045	2050
Cell	Energy	% of 2020	100%	86%	71%	63%	55%	55%	55%
Cathode	Energy	% of 2020	100%	86%	71%	63%	55%	55%	55%

The energy density of batteries is another important consideration when analysing energy and material use in production per kWh of battery. As the energy density improves (more kWh per kg of battery), the energy use per kWh battery production decreases, as it is linked to the mass of the battery produced. Energy densities for the different battery types have been estimated from available information in the literature and feedback from stakeholders (Table A44). Pack energy densities for traditional battery types (NCA, NMC, LFP and LMO) are taken from the latest bill of materials (BOMs) in GREET and converted to cell energy densities with consideration of the cell weight share of total pack. Advanced battery types, including solid state and sodium ion, have also been included with energy densities of solid-state battery chemistries roughly double that of the traditional battery types while sodium ion is assumed to be like NMC. The benefits of sodium ion batteries relate to sodium being an abundant resource and the possibility to yield much faster charging times.

Table A44: Energy densities of different battery types in base year (2020)

BatType	Units	Pack	Cell	Source
NCA	Wh/kg	132	224	(1)
NMC	Wh/kg	126	206	(1)
LFP	Wh/kg	98	159	(1)
LMO	Wh/kg	103	161	(1)
NCA-SS	Wh/kg	264	448	(1)
NMC-SS	Wh/kg	252	413	(1)
LMO-SS	Wh/kg	206	321	(1)
LVO-SS	Wh/kg	372	580	(2)
Na-ion	Wh/kg	126	206	(3)

Notes: '-SS' denotes a battery with a solid-state electrolyte.

Source: (1) Based on GREET (ANL, 2018), adjusted to higher 2020 BEV market model reported energy density performance. (2) Based on (Lastoskie, 2015). (3) assumed to be similar to NMC Li-ion, based on (Peters J. B., 2016).

In the model, a total battery pack energy density is calculated from an assumed mix of battery chemistries presented in the table above. As shown in Table A45, an increase in total pack energy density is calculated over time, which results from changes in the mix of battery chemistries (i.e. increasing penetration of advanced batteries over time – summarised in the main report in Chapter 4), and some overall improvements in the energy density of each battery types (based on consultation with Ricardo's battery experts).

Table A45: Total battery pack energy density (Wh/kg)

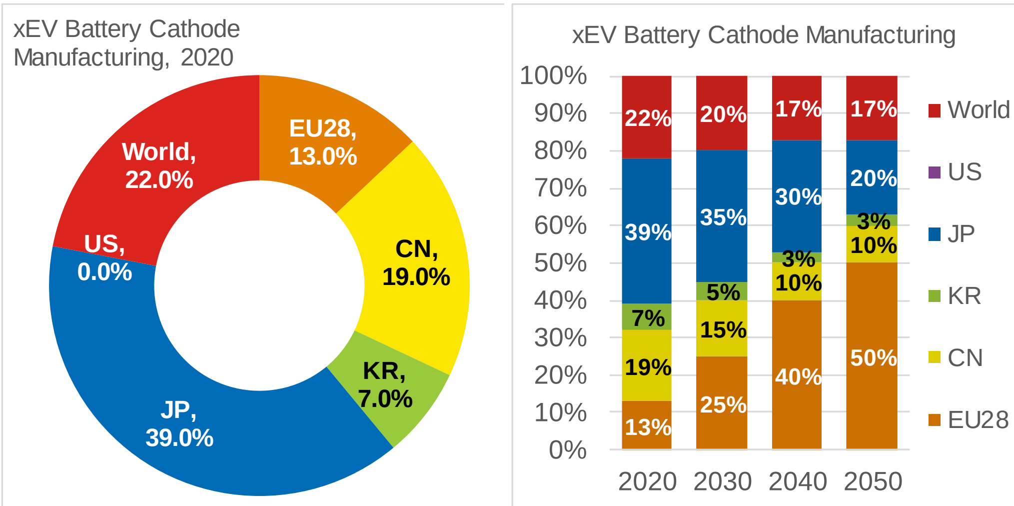
	2020	2030	2040	2050
Default	122	284	494	600
Low	122	233	397	447
High	122	328	558	708

Finally, the calculation of GWP impact from manufacturing stages of the battery must account for where production is taking place and the subsequent carbon intensity of electricity generation. Figure A59 below, shows the manufacturing location mix for battery cathode formation, battery cell manufacturing and battery pack assembly in the default scenario.

The additional foreground assumptions for the materials used in battery manufacturing are also provided in Table A46.

Figure A59: Baseline scenario assumptions for regional battery manufacturing

Battery Cathode:



Battery Cell:

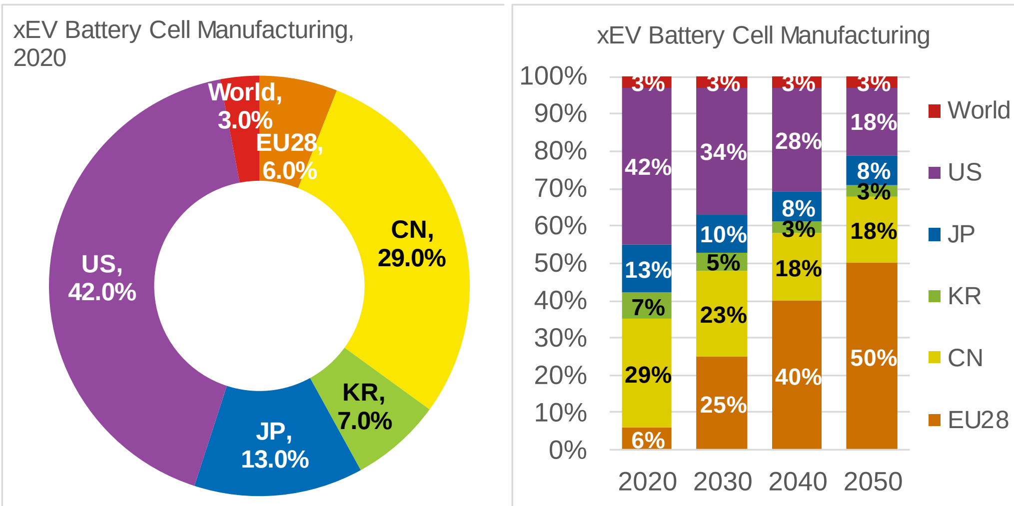
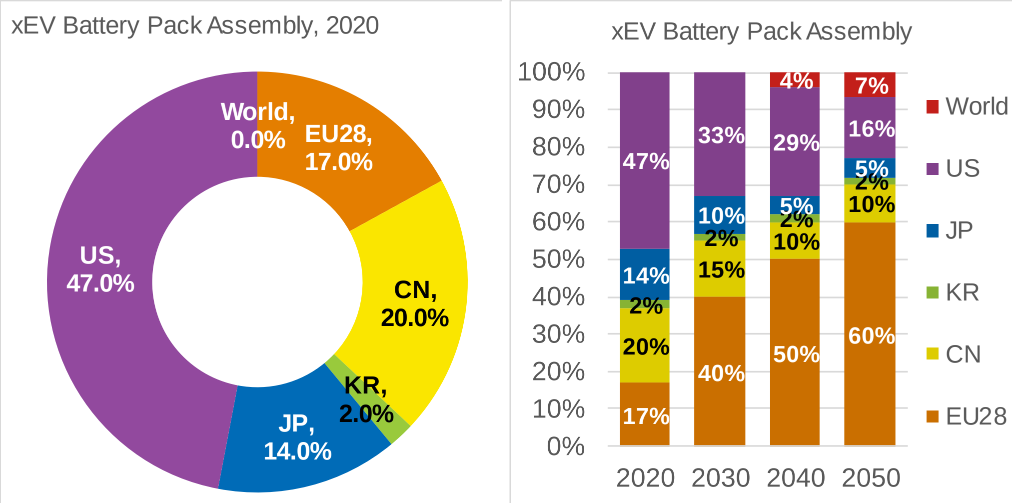


Figure A59: Baseline scenario assumptions for regional battery manufacturing

Pack Assembly:



Sources: 2020 shares based on information from (Ricardo Energy & Environment, 2019); future projections are illustrative scenarios for a shift towards EU battery manufacturing to supply local EU vehicle production developed by Ricardo.

Table A46: Battery manufacturing and EoL: Recycled content, recycling rate and material loss factor assumptions by material (Default, EUSVC)

	Use Factor*	RContent, R1	Recycling Recovery, R2						
	Default	Default	Default assumptions				EU SVC Sensitivity**		
Material	2020	2020	2020	2025	2030	2040	2025	2030	2040
Steel (low alloy)	108%	54%	90%	90%	90%	90%	90%	90%	90%
Iron	108%	54%	90%	90%	90%	90%	90%	90%	90%
Aluminium	102%	33%	0%	30%	60%	90%	45%	90%	90%
Lithium	100%	0%	0%	30%	60%	90%	45%	90%	94%
Titanium	100%	54%	0%	30%	60%	90%	45%	90%	90%
Cobalt	108%	0%	94%	95%	97%	98%	96%	98%	98%
Copper	111%	72%	98%	98%	98%	98%	98%	98%	98%
Lead	100%	62%	0%	0%	0%	0%	0%	0%	0%
Manganese	108%	0%	95%	96%	97%	98%	97%	98%	98%
Nickel	108%	0%	95%	96%	97%	98%	97%	98%	98%
CarbonFRP	100%	10%	0%	3%	7%	10%	15%	30%	50%
Plastic: Average	100%	0%	0%	17%	33%	50%	25%	50%	90%
Plastic: PE	102%	0%	0%	17%	33%	50%	25%	50%	90%
Plastic: PP	102%	0%	0%	17%	33%	50%	25%	50%	90%
Binder: PTFE	100%	0%	0%	0%	0%	0%	0%	0%	0%
Coolant: Propylene Glycol	100%	0%	0%	17%	33%	50%	25%	50%	50%
Water	100%	0%	0%	0%	0%	0%	0%	0%	0%
Thermal insulation	100%	0%	0%	0%	0%	0%	0%	0%	0%

	Use Factor*	RContent, R1	Recycling Recovery, R2						
	Default	Default	Default assumptions				EU SVC Sensitivity**		
Material	**2020**	**2020**	**2020**	**2025**	**2030**	**2040**	**2025**	**2030**	**2040**
Electrolyte: Dimethyl Carbonate	106%	0%	0%	17%	33%	50%	25%	50%	90%
Electrolyte: Ethylene Carbonate	106%	0%	0%	17%	33%	50%	25%	50%	90%
Graphite/Carbon	108%	0%	0%	30%	60%	90%	45%	90%	90%
Hydrochloric Acid	100%	0%	0%	0%	0%	0%	0%	0%	0%
Hydrogen Peroxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
LiPF6	100%	0%	0%	0%	0%	0%	0%	0%	0%
LiPON	100%	0%	0%	0%	0%	0%	0%	0%	0%
Lime (CaO)	100%	0%	0%	0%	0%	0%	0%	0%	0%
Lithium Carbonate	100%	0%	0%	0%	0%	0%	0%	0%	0%
Lithium Hydroxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Magnesium Hydroxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Manganese Oxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Manganese Sulphate	100%	0%	0%	0%	0%	0%	0%	0%	0%
NaPF6	100%	0%	0%	0%	0%	0%	0%	0%	0%
Nickel Sulphate	100%	0%	0%	0%	0%	0%	0%	0%	0%
NMP	100%	0%	0%	0%	0%	0%	0%	0%	0%
Oxygen	100%	0%	0%	0%	0%	0%	0%	0%	0%
Phosphoric Acid	100%	0%	0%	0%	0%	0%	0%	0%	0%
Phosphorus	100%	0%	0%	0%	0%	0%	0%	0%	0%
Silicon	100%	0%	0%	0%	0%	0%	0%	0%	0%
Sodium	108%	0%	0%	30%	60%	90%	45%	90%	90%
Sodium Hydroxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Sulphuric Acid	100%	0%	0%	0%	0%	0%	0%	0%	0%
Titanium Dioxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Vanadium	100%	0%	0%	30%	60%	90%	45%	90%	90%
Vanadium Oxide	100%	0%	0%	0%	0%	0%	0%	0%	0%
Misc Other	100%	0%	0%	0%	0%	0%	0%	0%	0%
Electronics	100%	0%	50%	50%	50%	50%	50%	50%	90%

Notes: * The 'Use Factor' is defined as the proportion of material used in manufacturing as a percentage of the content in the finished component/vehicle – i.e. values are greater than 100% where losses are assumed. In the SVC** sensitivity, by 2030 the material use in vehicle/component manufacturing for steel is assumed to reduce to 114% of the vehicle content, and for aluminium it is reduced to 105% of the vehicle content. ** SVC = Sustainable Value Chain sensitivity.

Source: Recycled content and recycling rates based on PEF Defaults (JRC, 2018a), and previous analysis by Ricardo in (Ricardo, 2018) and (Ricardo Energy & Environment, 2019). Assumptions for material losses based on (IEA, 2019) for aluminium and steel, and the GREET model (ANL, 2018) for other battery materials.

A4.3.3 Vehicle operation and maintenance

Table A47: Matrix summarising key sources and quality for vehicle operation calculations

High	Medium	Low	N/A

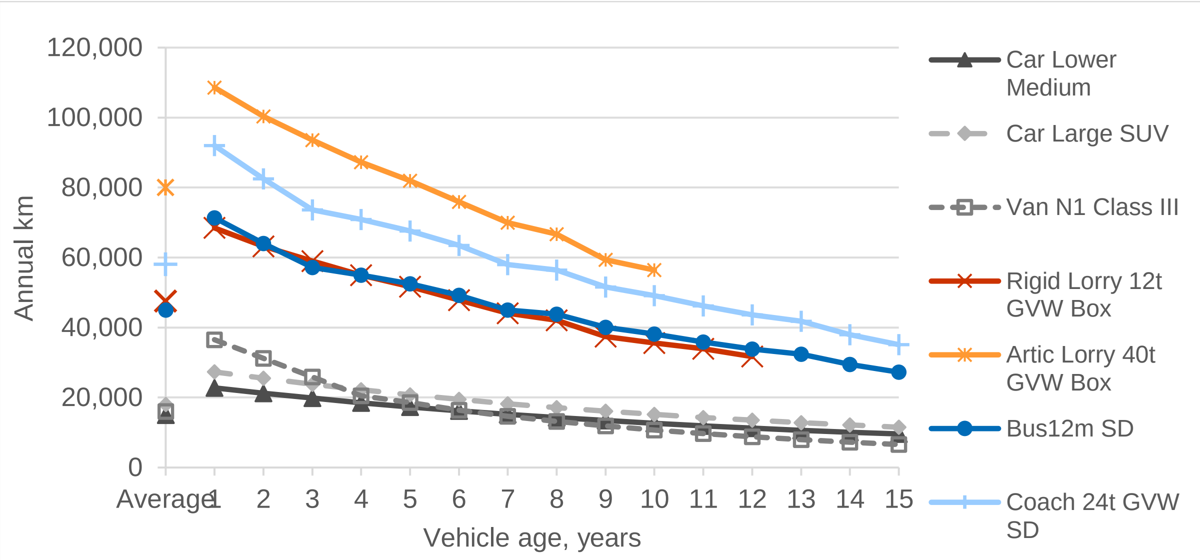
Parameters	Cars	Vans	Rigid	Artic	Bus	Coach
Lifetime and mileage	H (1)	H (1)	H (2)	H (2)	H (2)	H (2)
Mileage by age	H (1)	H (1)	M (3)	M (3)	M (3)	M (3)
Road vehicle shares	H (4)	H (4)	M (4)	M (4)	M (4)	M (4)
TC-RW	H (5)	H (5)	L*	L*	L*	L*
Energy consumption variation by road type	H (6, 7)	H (6, 7)	H (6) /M (7, 8)	H (6) /M (7, 8)	H (6) /M (7, 8)	H (6) /M (7, 8)
Electric range	H (9)	H (9)	M (10)	M (10)	M (10)	M (10)
Exhaust emissions	H (6, 7)	H (6, 7)	H (6) /M (7)	H (6) /M (7)	H (6) /M (7)	H (6) /M (7)
Ambient temperature sensitivity	M (12)	M (12)	N/A**	N/A**	N/A**	N/A**
Component/consumable replacement frequency	M (13)	M (13)	M (13)	M (13)	M (13)	M (13)

Sources: * No data available, so based purely on the difference in operation on different road types in the real-world, versus the defined regulatory cycle. ** no suitable data available to allow for a sensitivity on this for HDVs.

#	Source	Quality	Comment
(1)	(CE Delft et al., 2017)	High	Based on results from studies for DG CLIMA on real-world mileage (Ricardo-AEA, 2014), (Ricardo-AEA, 2014a) and second hand vehicles (TML et al, 2016).
(2)	(Ricardo Energy & Environment et al., 2015)	High	Detailed analysis of lightweighting and the development of a MACC (marginal abatement cost-curve) model to assess cost-effectiveness, including mileage profiles and lifetimes for heavy duty vehicles. Key assumptions reviewed and tested with industry stakeholders.
(3)	(Emisia, 2013)	Medium	Ricardo analysis of road transport datasets for heavy duty vehicles. Underlying mileage by age is old and based on poorer statistics than the utilised LDV mileage studies. Dataset have also been used to calibrate models used in EC impact assessment, such as PRIMES-TREMOVE.
(4)	PRIME-TREMOVE (2018), TREMOVE (2012)	High /Medium	Urban/Rural/Motorway shares based on datasets for different vehicle categories on the shares of mileage on different road types provided by the EC for the tow modelling scenarios also used in this study for other analyses. Datasets for heavy duty vehicles are typically of lower confidence, with some unusual/counter-intuitive distributions. Shares for interurban were split into rural and motorway based on older datasets from the TREMOVE model.
(5)	(Ricardo Energy & Environment et al., 2018)	High	NEDC-WLTP and WLTP-Real-World correlation factors by vehicle size and powertrain type for passenger cars and vans, based on EC DG JRC analysis.
(6)	(Emisia, 2019)	High	Derived from COPERT speed-fuel consumption curves for different LDV and HDV powertrains. Not all newer powertrain types are covered for all vehicle types, so data has to be supplemented from other sources.
(7)	(Ricardo Energy & Environment, 2015)	Medium	Development of speed-energy consumption and emission (NOx, PM) profiles for a series of alternative fuel powertrains not covered by COPERT, in part based on vehicle simulation analyses.

#	Source	Quality	Comment
(8)	Ricardo (2019)	Medium	No real-world data was available for the energy consumption profiles for certain alternative fuel powertrains (i.e. certain gas-fuelled vehicles, hybrids and xEVs), Ricardo carried out some simulation analysis using VECTO and additional post-processing of diesel ICEVs outputs to calculate hybrid and electric vehicle energy consumption profiles in relation to ICEVs.
(9)	Ricardo (2019)	High	Current typical xEV WLTP electric range assumptions for LDVs are based on a review of typical new models available on the EU market in 2019/2020.
(10)	(Ricardo Energy & Environment, 2019)	Medium	Assumptions for the electric range of actual and theoretical xEV heavy-duty vehicles was based on Ricardo's previous analysis for UK CCC, and a survey of current and forthcoming (/announced) models.
(11)	(JRC, 2016)	High	Assumptions for ICEV/HEV/PHEV charge-sustaining mode operation are based on temperature /fuel consumption relationships from JRC analysis.
(12)	(Volkswagen, 2020)	Medium	Assumptions for electric operation are based on the temperature-electric range profile with/without a heat-pump for the VW ID.3 BEV provided by Volkswagen in material for ID.3 pre-bookers.
(13)	(ANL, 2018), various others	Medium	Assumptions for the characterisation and frequency of replacements for key components (e.g. tyres, exhaust, etc.) and for consumables (i.e. oil, coolant, transmission fluids, etc.) were taken from a range of sources, and supplemented by Ricardo's own judgement/experience where gaps existed.

Table A48: Vehicle lifetime and mileage/age profile, by vehicle type



Source: (CE Delft et al., 2017), (Ricardo Energy & Environment et al., 2015) and (Emisia, 2013).

Table A49: Test-cycle to real-world conversion factors (TC/Cycle1 = default regulatory cycle, Cycle2 = alternative cycle)

Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Car Lower Medium	ICEV-G	Fuel1	Gasoline	119.6%	137.0%
Car Lower Medium	ICEV-D	Fuel1	Diesel	113.4%	137.0%
Car Lower Medium	ICEV-CNG	Fuel1	CNG	100.8%	137.0%
Car Lower Medium	ICEV-LPG	Fuel1	LPG	118.2%	137.0%
Car Lower Medium	ICEV-LNG	Fuel1	LNG	100.0%	100.0%
Car Lower Medium	ICEV-CNGL	Fuel1	CNG	100.0%	100.0%
Car Lower Medium	ICEV-LNGD	Fuel1	LNG	100.0%	100.0%
Car Lower Medium	HEV-G	Fuel1	Gasoline	109.7%	145.0%
Car Lower Medium	HEV-D	Fuel1	Diesel	108.4%	145.0%
Car Lower Medium	PHEV-G	Fuel1	Gasoline	109.7%	145.0%
Car Lower Medium	PHEV-D	Fuel1	Diesel	108.4%	145.0%
Car Lower Medium	BEV	Fuel1	Electricity	113.0%	145.0%
Car Lower Medium	FCEV	Fuel1	Hydrogen	113.0%	145.0%
Car Lower Medium	HEV-D-ERS	Fuel1	Diesel	100.0%	100.0%
Car Lower Medium	BEV-ERS	Fuel1	Electricity	100.0%	100.0%
Car Lower Medium	FC-REEV	Fuel1	Hydrogen	113.0%	145.0%
Car Lower Medium	ICEV-G	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-D	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	ICEV-LNGD	Fuel2	Diesel	100.0%	100.0%
Car Lower Medium	HEV-G	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	HEV-D	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	PHEV-G	Fuel2	Electricity	113.0%	145.0%
Car Lower Medium	PHEV-D	Fuel2	Electricity	113.0%	145.0%
Car Lower Medium	BEV	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	FCEV	Fuel2	N/A	100.0%	100.0%
Car Lower Medium	HEV-D-ERS	Fuel2	Electricity	100.0%	100.0%
Car Lower Medium	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Car Lower Medium	FC-REEV	Fuel2	Electricity	113.0%	145.0%
Car Large SUV	ICEV-G	Fuel1	Gasoline	128.4%	137.0%
Car Large SUV	ICEV-D	Fuel1	Diesel	120.1%	137.0%
Car Large SUV	ICEV-CNG	Fuel1	CNG	100.8%	137.0%

Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Car Large SUV	ICEV-LPG	Fuel1	LPG	118.2%	137.0%
Car Large SUV	ICEV-LNG	Fuel1	LNG	100.0%	100.0%
Car Large SUV	ICEV-CNGL	Fuel1	CNG	100.0%	100.0%
Car Large SUV	ICEV-LNGD	Fuel1	LNG	100.0%	100.0%
Car Large SUV	HEV-G	Fuel1	Gasoline	117.5%	145.0%
Car Large SUV	HEV-D	Fuel1	Diesel	111.7%	145.0%
Car Large SUV	PHEV-G	Fuel1	Gasoline	117.5%	145.0%
Car Large SUV	PHEV-D	Fuel1	Diesel	111.7%	145.0%
Car Large SUV	BEV	Fuel1	Electricity	111.7%	145.0%
Car Large SUV	FCEV	Fuel1	Hydrogen	111.7%	145.0%
Car Large SUV	HEV-D-ERS	Fuel1	Diesel	100.0%	100.0%
Car Large SUV	BEV-ERS	Fuel1	Electricity	100.0%	100.0%
Car Large SUV	FC-REEV	Fuel1	Hydrogen	111.7%	145.0%
Car Large SUV	ICEV-G	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-D	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Car Large SUV	ICEV-LNGD	Fuel2	Diesel	100.0%	100.0%
Car Large SUV	HEV-G	Fuel2	N/A	100.0%	100.0%
Car Large SUV	HEV-D	Fuel2	N/A	100.0%	100.0%
Car Large SUV	PHEV-G	Fuel2	Electricity	111.7%	145.0%
Car Large SUV	PHEV-D	Fuel2	Electricity	111.7%	145.0%
Car Large SUV	BEV	Fuel2	N/A	100.0%	100.0%
Car Large SUV	FCEV	Fuel2	N/A	100.0%	100.0%
Car Large SUV	HEV-D-ERS	Fuel2	Electricity	100.0%	100.0%
Car Large SUV	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Car Large SUV	FC-REEV	Fuel2	Electricity	111.7%	145.0%
Van N1 Class III	ICEV-G	Fuel1	Gasoline	109.4%	133.0%
Van N1 Class III	ICEV-D	Fuel1	Diesel	101.9%	133.0%
Van N1 Class III	ICEV-CNG	Fuel1	CNG	97.9%	133.0%
Van N1 Class III	ICEV-LPG	Fuel1	LPG	114.7%	133.0%
Van N1 Class III	ICEV-LNG	Fuel1	LNG	100.0%	100.0%
Van N1 Class III	ICEV-CNGL	Fuel1	CNG	100.0%	100.0%
Van N1 Class III	ICEV-LNGD	Fuel1	LNG	100.0%	100.0%
Van N1 Class III	HEV-G	Fuel1	Gasoline	104.9%	145.0%
Van N1 Class III	HEV-D	Fuel1	Diesel	99.9%	145.0%

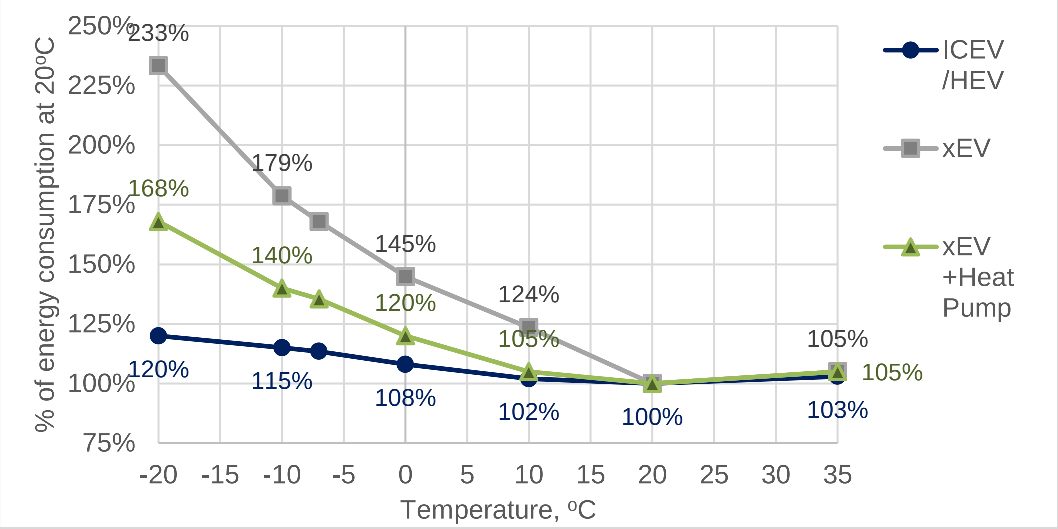
Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Van N1 Class III	PHEV-G	Fuel1	Gasoline	104.9%	145.0%
Van N1 Class III	PHEV-D	Fuel1	Diesel	99.9%	145.0%
Van N1 Class III	BEV	Fuel1	Electricity	119.8%	145.0%
Van N1 Class III	FCEV	Fuel1	Hydrogen	119.8%	145.0%
Van N1 Class III	HEV-D-ERS	Fuel1	Diesel	100.0%	100.0%
Van N1 Class III	BEV-ERS	Fuel1	Electricity	100.0%	100.0%
Van N1 Class III	FC-REEV	Fuel1	Hydrogen	119.8%	145.0%
Van N1 Class III	ICEV-G	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-D	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	ICEV-LNGD	Fuel2	Diesel	100.0%	100.0%
Van N1 Class III	HEV-G	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	HEV-D	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	PHEV-G	Fuel2	Electricity	119.8%	145.0%
Van N1 Class III	PHEV-D	Fuel2	Electricity	119.8%	145.0%
Van N1 Class III	BEV	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	FCEV	Fuel2	N/A	100.0%	100.0%
Van N1 Class III	HEV-D-ERS	Fuel2	Electricity	100.0%	100.0%
Van N1 Class III	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Van N1 Class III	FC-REEV	Fuel2	Electricity	119.8%	145.0%
Rigid Lorry 12t GVW Box	ICEV-G	Fuel1	Gasoline	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-D	Fuel1	Diesel	76.7%	101.4%
Rigid Lorry 12t GVW Box	ICEV-CNG	Fuel1	CNG	76.7%	101.4%
Rigid Lorry 12t GVW Box	ICEV-LPG	Fuel1	LPG	76.7%	101.4%
Rigid Lorry 12t GVW Box	ICEV-LNG	Fuel1	LNG	76.7%	101.4%
Rigid Lorry 12t GVW Box	ICEV-CNGL	Fuel1	CNG	76.7%	101.4%
Rigid Lorry 12t GVW Box	ICEV-LNGD	Fuel1	LNG	76.7%	101.4%
Rigid Lorry 12t GVW Box	HEV-G	Fuel1	Gasoline	100.0%	100.0%
Rigid Lorry 12t GVW Box	HEV-D	Fuel1	Diesel	89.2%	97.4%
Rigid Lorry 12t GVW Box	PHEV-G	Fuel1	Gasoline	100.0%	100.0%
Rigid Lorry 12t GVW Box	PHEV-D	Fuel1	Diesel	89.2%	97.4%
Rigid Lorry 12t GVW Box	BEV	Fuel1	Electricity	127.5%	86.3%
Rigid Lorry 12t GVW Box	FCEV	Fuel1	Hydrogen	127.5%	86.3%
Rigid Lorry 12t GVW Box	HEV-D-ERS	Fuel1	Diesel	89.2%	89.2%
Rigid Lorry 12t GVW Box	BEV-ERS	Fuel1	Electricity	100.0%	100.0%

Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Rigid Lorry 12t GVW Box	FC-REEV	Fuel1	Hydrogen	127.5%	127.5%
Rigid Lorry 12t GVW Box	ICEV-G	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-D	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	ICEV-LNGD	Fuel2	Diesel	76.7%	101.4%
Rigid Lorry 12t GVW Box	HEV-G	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	HEV-D	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	PHEV-G	Fuel2	Electricity	127.5%	86.3%
Rigid Lorry 12t GVW Box	PHEV-D	Fuel2	Electricity	127.5%	86.3%
Rigid Lorry 12t GVW Box	BEV	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	FCEV	Fuel2	N/A	100.0%	100.0%
Rigid Lorry 12t GVW Box	HEV-D-ERS	Fuel2	Electricity	100.0%	100.0%
Rigid Lorry 12t GVW Box	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Rigid Lorry 12t GVW Box	FC-REEV	Fuel2	Electricity	127.5%	86.3%
Artic Lorry 40t GVW Box	ICEV-G	Fuel1	Gasoline	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-D	Fuel1	Diesel	143.4%	129.4%
Artic Lorry 40t GVW Box	ICEV-CNG	Fuel1	CNG	143.4%	129.4%
Artic Lorry 40t GVW Box	ICEV-LPG	Fuel1	LPG	143.4%	129.4%
Artic Lorry 40t GVW Box	ICEV-LNG	Fuel1	LNG	143.4%	129.4%
Artic Lorry 40t GVW Box	ICEV-CNGL	Fuel1	CNG	143.4%	129.4%
Artic Lorry 40t GVW Box	ICEV-LNGD	Fuel1	LNG	143.4%	129.4%
Artic Lorry 40t GVW Box	HEV-G	Fuel1	Gasoline	100.0%	100.0%
Artic Lorry 40t GVW Box	HEV-D	Fuel1	Diesel	122.0%	120.6%
Artic Lorry 40t GVW Box	PHEV-G	Fuel1	Gasoline	100.0%	100.0%
Artic Lorry 40t GVW Box	PHEV-D	Fuel1	Diesel	122.0%	120.6%
Artic Lorry 40t GVW Box	BEV	Fuel1	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	FCEV	Fuel1	Hydrogen	95.3%	98.4%
Artic Lorry 40t GVW Box	HEV-D-ERS	Fuel1	Diesel	122.0%	122.0%
Artic Lorry 40t GVW Box	BEV-ERS	Fuel1	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	FC-REEV	Fuel1	Hydrogen	95.3%	95.3%
Artic Lorry 40t GVW Box	ICEV-G	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-D	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-LNG	Fuel2	N/A	100.0%	100.0%

Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Artic Lorry 40t GVW Box	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	ICEV-LNGD	Fuel2	Diesel	143.4%	129.4%
Artic Lorry 40t GVW Box	HEV-G	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	HEV-D	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	PHEV-G	Fuel2	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	PHEV-D	Fuel2	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	BEV	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	FCEV	Fuel2	N/A	100.0%	100.0%
Artic Lorry 40t GVW Box	HEV-D-ERS	Fuel2	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	BEV-ERS	Fuel2	Electricity	95.3%	98.4%
Artic Lorry 40t GVW Box	FC-REEV	Fuel2	Electricity	95.3%	98.4%
Bus 12m SD	ICEV-G	Fuel1	Gasoline	100.0%	100.0%
Bus 12m SD	ICEV-D	Fuel1	Diesel	102.4%	102.4%
Bus 12m SD	ICEV-CNG	Fuel1	CNG	102.4%	102.4%
Bus 12m SD	ICEV-LPG	Fuel1	LPG	102.4%	102.4%
Bus 12m SD	ICEV-LNG	Fuel1	LNG	102.4%	102.4%
Bus 12m SD	ICEV-CNGL	Fuel1	CNG	102.4%	102.4%
Bus 12m SD	ICEV-LNGD	Fuel1	LNG	102.4%	102.4%
Bus 12m SD	HEV-G	Fuel1	Gasoline	100.0%	100.0%
Bus 12m SD	HEV-D	Fuel1	Diesel	95.6%	95.6%
Bus 12m SD	PHEV-G	Fuel1	Gasoline	100.0%	100.0%
Bus 12m SD	PHEV-D	Fuel1	Diesel	95.6%	95.6%
Bus 12m SD	BEV	Fuel1	Electricity	101.0%	101.0%
Bus 12m SD	FCEV	Fuel1	Hydrogen	101.0%	101.0%
Bus 12m SD	HEV-D-ERS	Fuel1	Diesel	95.6%	95.6%
Bus 12m SD	BEV-ERS	Fuel1	Electricity	101.0%	101.0%
Bus 12m SD	FC-REEV	Fuel1	Hydrogen	101.0%	101.0%
Bus 12m SD	ICEV-G	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-D	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	ICEV-LNGD	Fuel2	Diesel	102.4%	102.4%
Bus 12m SD	HEV-G	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	HEV-D	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	PHEV-G	Fuel2	Electricity	101.0%	101.0%
Bus 12m SD	PHEV-D	Fuel2	Electricity	101.0%	101.0%

Vehicle Type	Powertrain	FuelNo	Fuel Type	TC_RW	Cycle2_RW
Bus 12m SD	BEV	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	FCEV	Fuel2	N/A	100.0%	100.0%
Bus 12m SD	HEV-D-ERS	Fuel2	Diesel	100.0%	100.0%
Bus 12m SD	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Bus 12m SD	FC-REEV	Fuel2	Electricity	101.0%	101.0%
Coach 24t GVW SD	ICEV-G	Fuel1	Gasoline	100.0%	100.0%
Coach 24t GVW SD	ICEV-D	Fuel1	Diesel	109.1%	109.1%
Coach 24t GVW SD	ICEV-CNG	Fuel1	CNG	109.1%	109.1%
Coach 24t GVW SD	ICEV-LPG	Fuel1	LPG	109.1%	109.1%
Coach 24t GVW SD	ICEV-LNG	Fuel1	LNG	109.1%	109.1%
Coach 24t GVW SD	ICEV-CNGL	Fuel1	CNG	109.1%	109.1%
Coach 24t GVW SD	ICEV-LNGD	Fuel1	LNG	109.1%	109.1%
Coach 24t GVW SD	HEV-G	Fuel1	Gasoline	100.0%	100.0%
Coach 24t GVW SD	HEV-D	Fuel1	Diesel	108.3%	108.3%
Coach 24t GVW SD	PHEV-G	Fuel1	Gasoline	100.0%	100.0%
Coach 24t GVW SD	PHEV-D	Fuel1	Diesel	108.3%	108.3%
Coach 24t GVW SD	BEV	Fuel1	Electricity	107.8%	107.8%
Coach 24t GVW SD	FCEV	Fuel1	Hydrogen	107.8%	107.8%
Coach 24t GVW SD	HEV-D-ERS	Fuel1	Diesel	108.3%	108.3%
Coach 24t GVW SD	BEV-ERS	Fuel1	Electricity	100.0%	100.0%
Coach 24t GVW SD	FC-REEV	Fuel1	Hydrogen	107.8%	107.8%
Coach 24t GVW SD	ICEV-G	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-D	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-CNG	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-LPG	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-LNG	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-CNGL	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	ICEV-LNGD	Fuel2	Diesel	109.1%	109.1%
Coach 24t GVW SD	HEV-G	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	HEV-D	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	PHEV-G	Fuel2	Electricity	107.8%	107.8%
Coach 24t GVW SD	PHEV-D	Fuel2	Electricity	107.8%	107.8%
Coach 24t GVW SD	BEV	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	FCEV	Fuel2	N/A	100.0%	100.0%
Coach 24t GVW SD	HEV-D-ERS	Fuel2	Diesel	100.0%	100.0%
Coach 24t GVW SD	BEV-ERS	Fuel2	Electricity	100.0%	100.0%
Coach 24t GVW SD	FC-REEV	Fuel2	Electricity	107.8%	107.8%

Figure A60: Summary chart on assumptions used in the ambient temperature variation sensitivity: Temperature dependence of light-duty vehicle energy consumption for ICE vs EV operation



Sources: Ricardo analysis based on (JRC, 2016) and (Volkswagen, 2020).

Table A50: Component and consumable replacement rate assumptions

Vehicle Type	Powertrain	Units*	Tyres	Engine Coolant	Engine Lubricant	Screen Wash	Other Liquids	Exhaust	CI-After-treatment	SI-After-treatment	SI-After-treatment-NG
All	ICEV-G	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	100%	**0%**
All	ICEV-D	% ICEV	100%	100%	100%	100%	100%	100%	100%	**0%**	**0%**
All	ICEV-LPG	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	100%	**0%**
All	ICEV-CNG	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	**0%**	100%
All	ICEV-LNG	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	**0%**	100%
All	ICEV-CNGL	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	**0%**	100%
All	ICEV-LNGD	% ICEV	100%	100%	100%	100%	100%	100%	100%	**0%**	100%
All	HEV-G	% ICEV	100%	100%	100%	100%	100%	100%	**0%**	100%	**0%**
All	HEV-D	% ICEV	100%	100%	100%	100%	100%	100%	100%	**0%**	**0%**
All	HEV-D-ERS	% ICEV	100%	100%	100%	100%	100%	100%	100%	**0%**	**0%**
All	PHEV-G	% ICEV	**110%**	100%	**50%**	100%	100%	**50%**	**0%**	**50%**	**0%**
All	PHEV-D	% ICEV	**110%**	100%	**50%**	100%	100%	**50%**	**50%**	**0%**	**0%**
All	BEV	% ICEV	**120%**	100%	**0%**	100%	100%	**0%**	**0%**	**0%**	**0%**
All	BEV-ERS	% ICEV	**110%**	100%	**0%**	100%	100%	**0%**	**0%**	**0%**	**0%**
All	FCEV	% ICEV	**110%**	100%	**0%**	100%	100%	**0%**	**0%**	**0%**	**0%**
All	FC-REEV	% ICEV	**110%**	100%	**0%**	100%	100%	**0%**	**0%**	**0%**	**0%**
Car Lower Medium	All	Replace km	45,000	45,000	20,000	5,000	100,000	150,000	150,000	150,000	150,000
Car Large SUV	All	Replace km	45,000	45,000	20,000	5,000	100,000	150,000	150,000	150,000	150,000
Van N1 Class III	All	Replace km	45,000	45,000	20,000	5,000	100,000	150,000	150,000	150,000	150,000
Rigid Lorry 12t GVW Box	All	Replace km	100,000	30,000	80,000	5,000	200,000	400,000	400,000	400,000	400,000
Artic Lorry 40t GVW Box	All	Replace km	120,000	30,000	80,000	5,000	300,000	600,000	600,000	600,000	600,000
Bus 12m SD	All	Replace km	50,000	30,000	50,000	5,000	300,000	500,000	500,000	500,000	500,000
Coach 24t GVW SD	All	Replace km	80,000	30,000	50,000	5,000	300,000	600,000	600,000	600,000	600,000

Notes: * Replacement frequencies/rates for alternative powertrains are scaled based on the reference ICEV powertrain. Replacement frequency is defined in terms of the ‘Replacement km’, which defines the point of replacement for every ‘n’ km over a vehicle lifetime. The total number of replacements required is therefore the integer value of the lifetime km / replacement frequency.

A4.3.4 Vehicle end-of-life (EoL)

Table A51: Matrix summarising key sources and quality for vehicle end-of-life calculations

High	Medium	Low	N/A

Parameters	Source(s)	Rating
PEF CFF parameters	PEF default values were used for the available materials and according to the guidance on the application of the PEF CFF (circular footprint formula) (JRC, 2018a). For the remaining materials Ricardo assigned appropriate values based on the PEF defaults. These were used to determine the impacts of recycling, recovery and disposal of materials using the second part of the PEF CFF for material, and the recovery and disposal parts (see Figure A43).	M
Recycling recovery rate (R2 from PEF CFF)	Recycling recovery rates are based on PEF Defaults (JRC, 2018a), and previous analysis by Ricardo in (Ricardo, 2018) and (Ricardo Energy & Environment, 2019). See also Table A41 for vehicles and Table A46 for batteries.	H/M
Material flow to EoL	Material flow to EoL was based on the calculated total material composition of the vehicle based on the individual component material compositions.	H
Material impacts	Material impacts were based on the datasets from background LCI databases (see Section A4.1), with future impacts estimated based on electricity decarbonisation scenarios – as outlined in the methodology Appendix Section A3.13.2.1.	H/M
Regional vehicle recycling mix	It is assumed by default that 95% of all vehicles are sent for disposal and recycling within the EU at the end of their life.	M
Vehicle recycling electricity mix/impacts	Assumes the EU average grid electricity mix, based on the assumption that most recycling and recovery occurs locally.	M
Vehicle recycling energy consumption	Data from GREET (ANL, 2018) was used for the electricity consumption from vehicle recycling processes. An improvement (reduction) of 20% in this is assumed by 2050.	H/M
Energy recovery share (R3 from PEF CFF)	For most materials, based on the PEF default share of incineration/energy recovery is 45% of the non-recycled/recovered material (JRC, 2018a). The exception is for plastics, where it is assumed that 90% of non-recycled material goes to energy recovery.	H/M
Waste disposal	The remaining share of material is assumed to be disposed of to landfill, based on the PEF CFF (i.e. Disposal = 1-R1-R2-R3).	H/M
Battery recycling electricity mix/impacts	Assumes the EU average grid electricity mix, based on the assumption that most recycling and recovery occurs locally.	M
Battery recycling process impacts	Battery recycling impacts (including material use, energy consumption and other impacts) were defined mostly based on the GREET (ANL, 2018) and EverBatt (ANL, 2018a) models. In the Default case it is assumed that there is a shift from predominantly pyrometallurgic recycling processes in 2020, to 100% hydrometallurgical recycling by 2035. This shift is assumed to happen by 2030 instead in the EU SVC sensitivity.	H/M

Parameters	Source(s)	Rating
Battery 2nd life credits	The net credits from battery repurposing and 2nd life applications were based on a high-level methodology developed by Ricardo for a project for DG JRC (Ricardo Energy & Environment, 2019). Key assumptions are summarised in Table A52.	M

Table A52: Assumptions for battery repurposing and second life, by vehicle end-of-life year

Sensitivity	Parameter	Unit	2030	2040	2050	2060	2070
All	2nd Lifetime	%New battery lifetime	50%	50%	50%	50%	50%
All	Repurposing impact	%New battery manufacturing impact	10%	10%	10%	10%	10%
All	EoL Capacity	%New battery capacity	70%	70%	70%	70%	70%
None	2nd Life Share	%All xEV batteries	0%	0%	0%	0%	0%
Low	Share	%All xEV batteries	20%	40%	40%	40%	40%
High	Share	%All xEV batteries	40%	80%	80%	80%	80%
All	Share	%All xEV batteries	100%	100%	100%	100%	100%
None	**Net Credit (calculated)***	**%New battery manufacturing impact**	**0%**	**0%**	**0%**	**0%**	**0%**
Low	**Net Credit (calculated)***	**%New battery manufacturing impact**	**5%**	**10%**	**10%**	**10%**	**10%**
High	**Net Credit (calculated)***	**%New battery manufacturing impact**	**10%**	**20%**	**20%**	**20%**	**20%**
All	**Net Credit (calculated)***	**%New battery manufacturing impact**	**25%**	**25%**	**25%**	**25%**	**25%**

Notes: * The calculated Net Credit for battery second life = (EoL Capacity * 2nd Life Share * 2nd Lifetime), minus Repurposing impact (as a % of the new battery manufacturing impact for the year the battery goes for 2nd life). Average net credits are based on the displacement of a newly manufactured battery in the year at which the vehicle reaches the end of its life / the battery is repurposed for its second life.

A5 Appendix 5: Additional results from the LCA

This Appendix provides a selection of additional results from the application of the LCA methodology, to complement the information provided in the main body of the report.

A5.1 Background LCI material impacts

The outputs from the future impact calculations for the background LCI material inventory are an important input into the vehicle manufacturing (where they contribute to the burden for manufacturing new vehicles) and end-of-life calculations (where they determine the relative credits for additional material recovery through recycling of materials).

A list of the main materials used in vehicles and batteries (and also for recycling processes) ranked according to their GWP impact per kg of material) is provided in Figure A61. This chart provides an illustration of the relative importance of the key materials used from a GHG perspective, but it should be kept in mind that their overall impact will also depend on the share of the total vehicle/battery mass that these materials represent. Many of the lightweight structural materials that are projected to be used in greater quantities in future vehicles (to improve operational energy consumption) are high up on this ranked list – e.g. particularly aluminium, magnesium and carbon fibre. In addition, a number of the materials used in xEV powertrains and their batteries are also high up the list (e.g. Lithium, Nd(Dy)FeB, Electronics, LiPF6, Nickel and Cobalt), however some of these are used in relatively small quantities in terms of the overall mass of the vehicle.

Certain materials also have particularly high impacts in other impact categories (e.g. illustrated in later charts), for example copper and electronic components as regards human toxicity (HTP) and mineral resource depletion (ARD_MM), and textiles and carbon fibre as regards water scarcity (WaterS).

Figure A61: Example of GWP-ranked Background LCI material impact factors for 2020 GWP impacts for materials used in the manufacturing of vehicles and batteries, and for recycling for the Baseline scenario

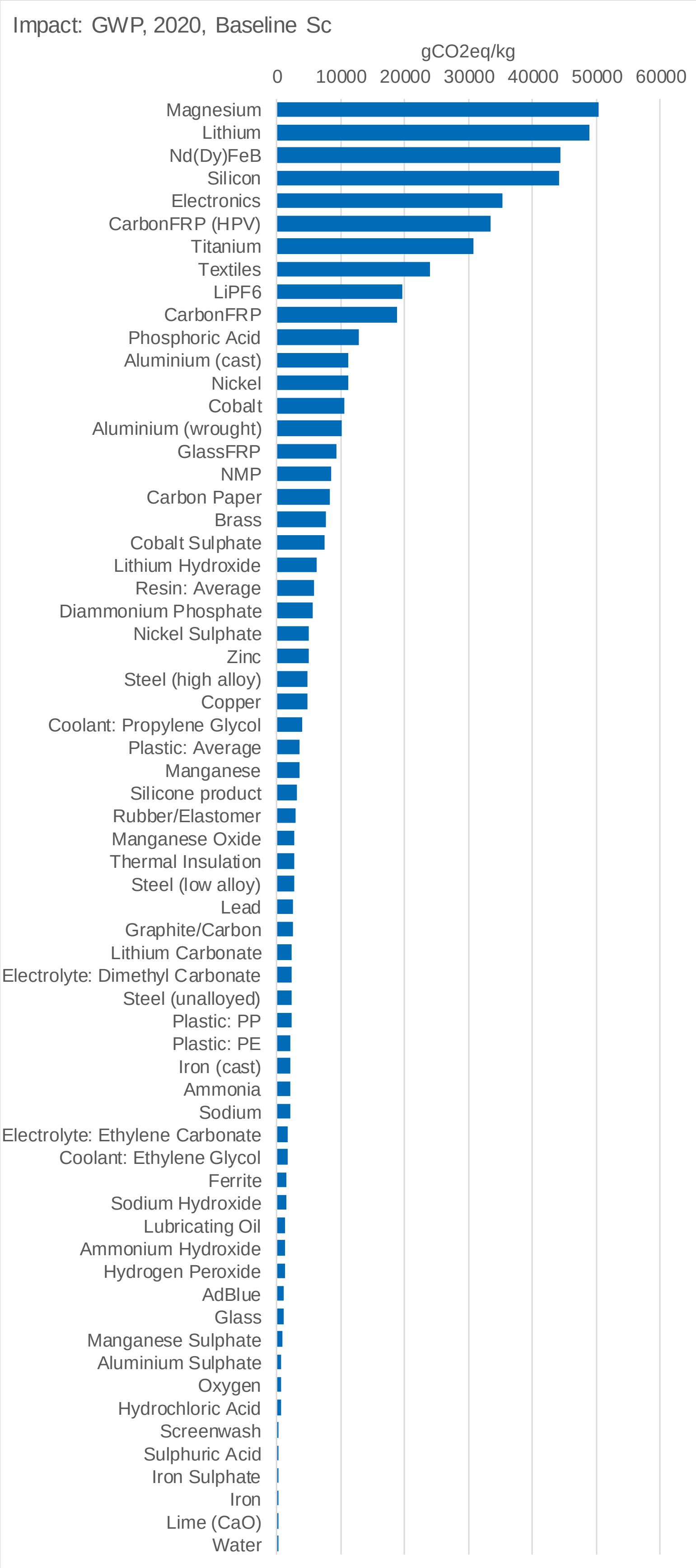


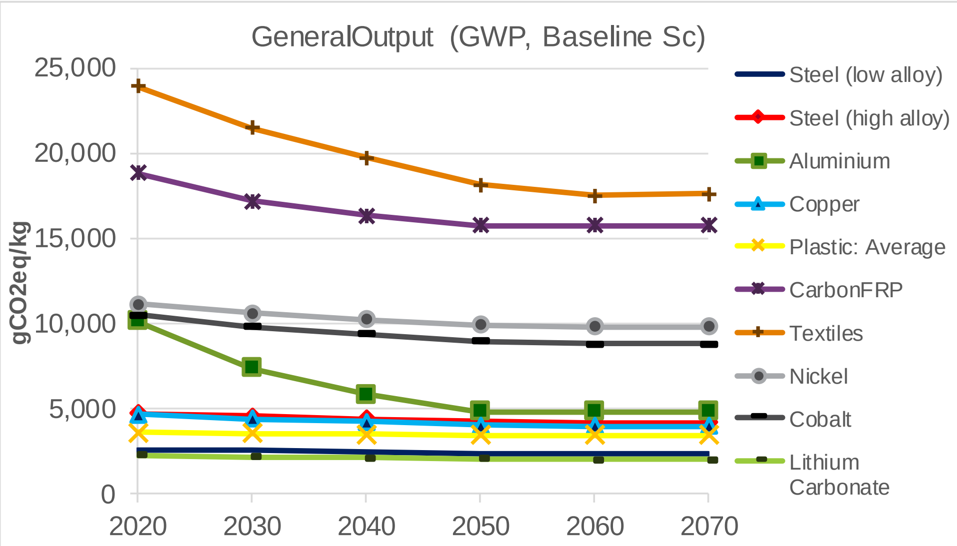
Figure A62 and Figure A63 provide a time-series illustration of how the GWP impacts (gCO2e/kg), resp. some other impacts for a subset containing some of the most important materials used in vehicle and battery manufacturing are projected to evolve over time under different scenarios. The future changes (reductions in impacts) are mainly affected by the projected evolution of the electricity generation mix.

Figure A62 shows that the impacts from primary/virgin aluminium production are projected to reduce more than those for primary steel production, as the former are more dependent on the electricity consumed. The reduction in impacts are greater in the Tech1.5 scenario (see Section 5.2) compared to the baseline, due to even higher power sector decarbonisation. In addition, the figure shows the significance of emissions resulting from textiles used in vehicles and for carbon fibre reinforced plastic (CarbonFRP). Carbon-fibre is used in compressed hydrogen storage vessels for fuel cell electric vehicles, and anticipated to be used to facilitate weight reduction in vehicles further in the future; it is a highly energy intensive production process using both electricity and other energy sources. Textile manufacturing is highly energy intensive, with Electric energy being one of the most commonly used energy types in textile and clothing plants (Palamutcu, 2010).

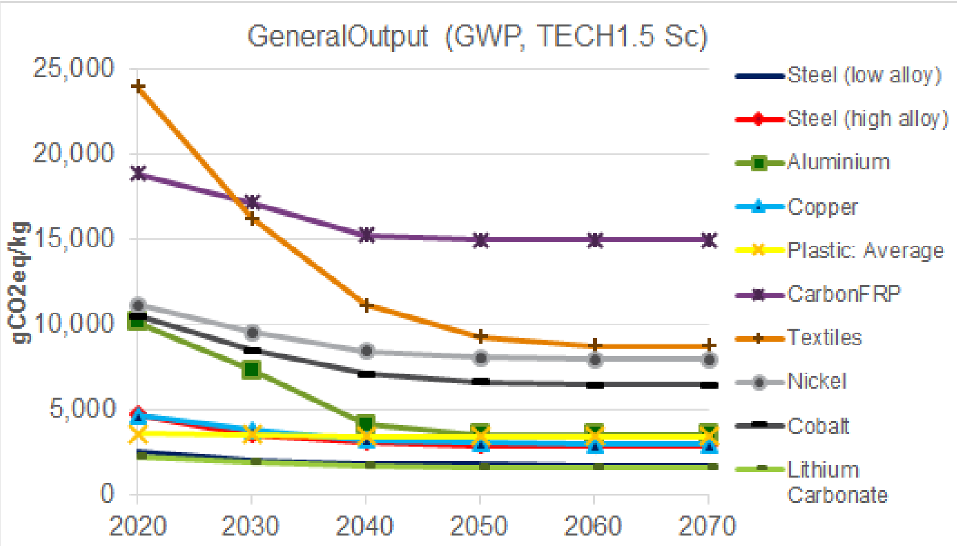
Figure A63 shows the high impacts (versus common structural materials) for PMF, HTP and ADP (abiotic depletion potential) for minerals & metals mid-points resulting from key materials used in electric vehicle components, including batteries (i.e. copper, nickel and cobalt). HTP and ADP impacts are directly linked to the material itself and not production, so don't change over time like many other impacts.

Figure A62: Selected time series impacts from key materials for GWP, (a) Baseline, (b) Tech1.5

(a) Baseline



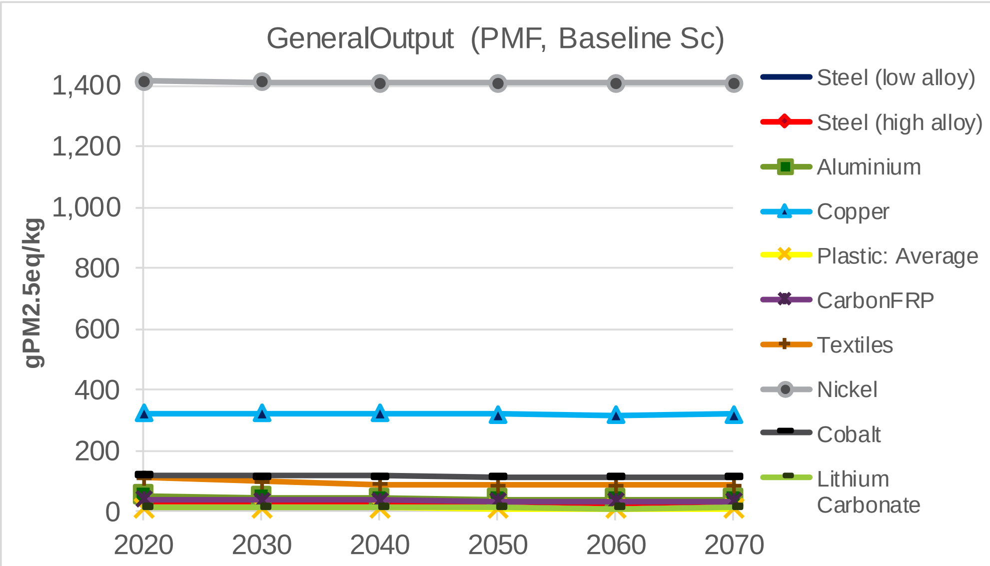
(b) Tech1.5



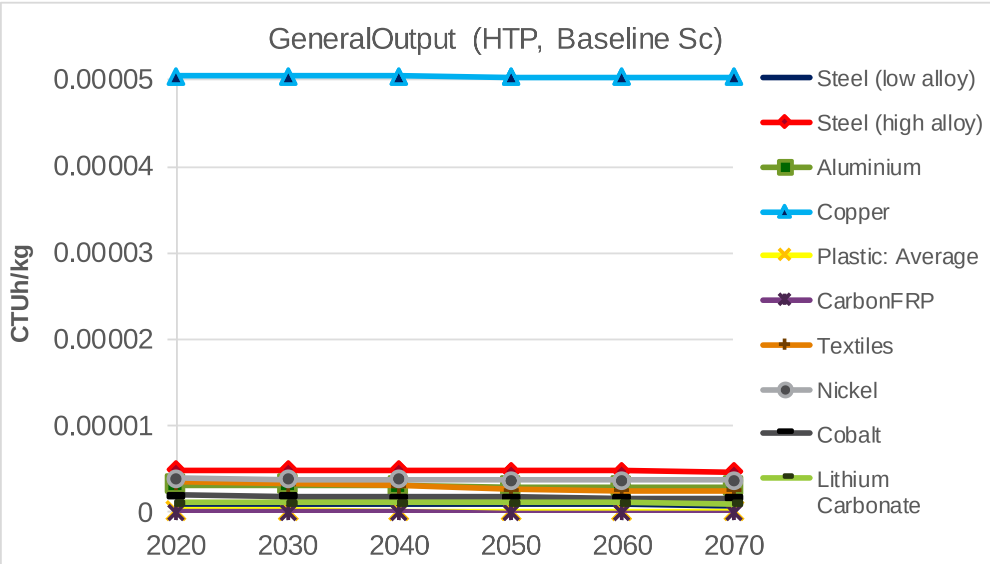
Notes: Results output from the vehicle LCA background LCI module.

Figure A63: Selected timeseries of other impacts from key materials for the Baseline scenario

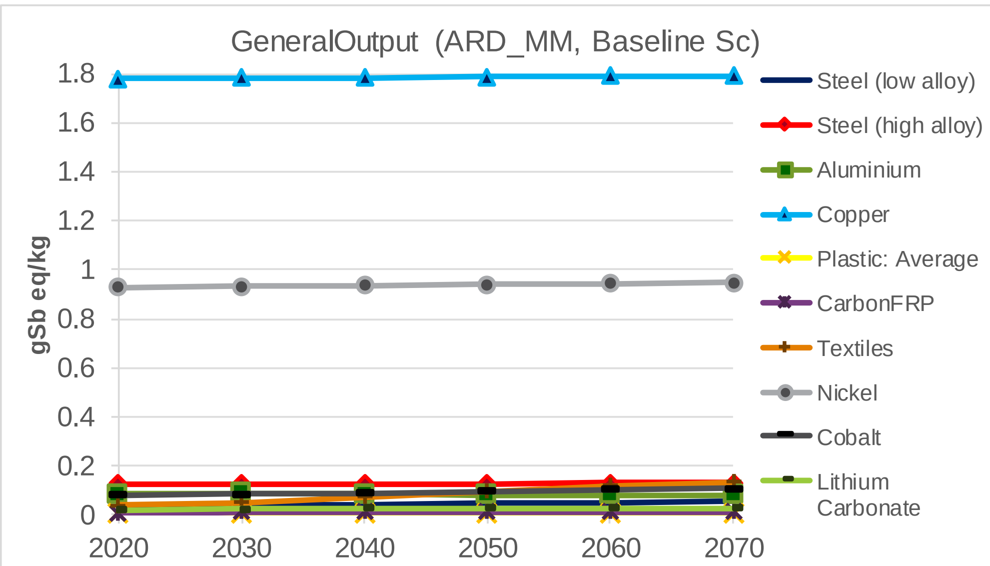
(a) PMF



(b) HTP



(c) ADP_MM



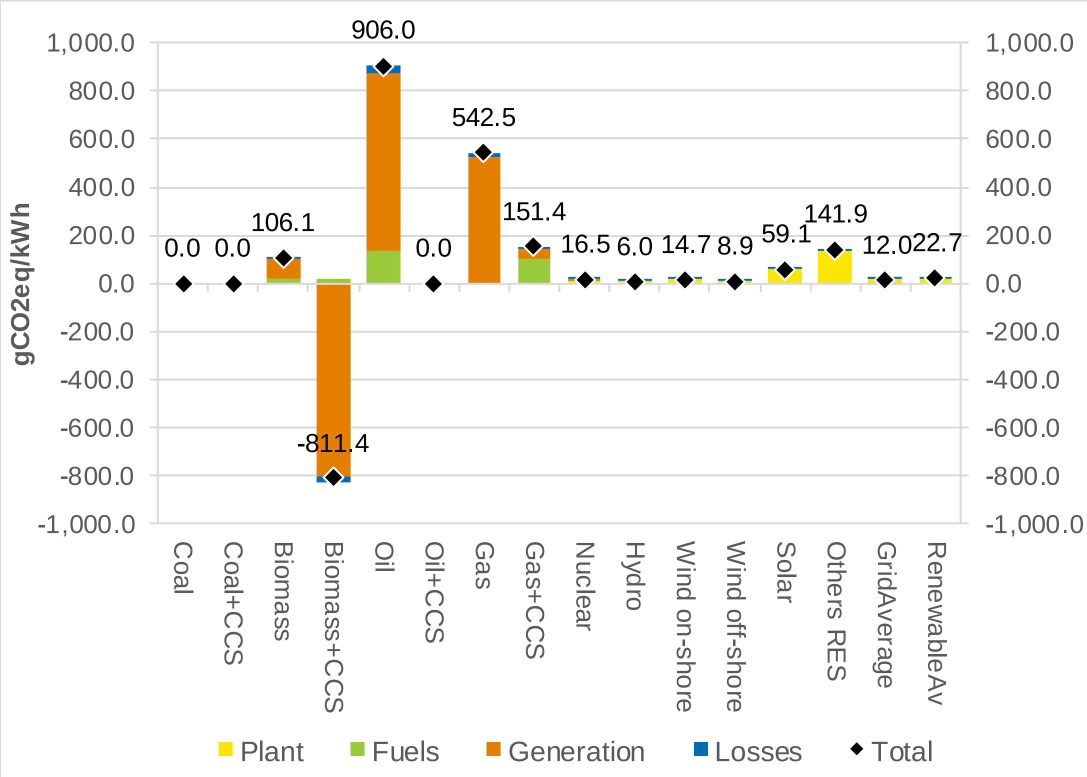
Notes: Results output from the vehicle LCA background LCI module.

A5.2 Electricity production chains

A5.2.1 Additional LCA results for different electricity generation types

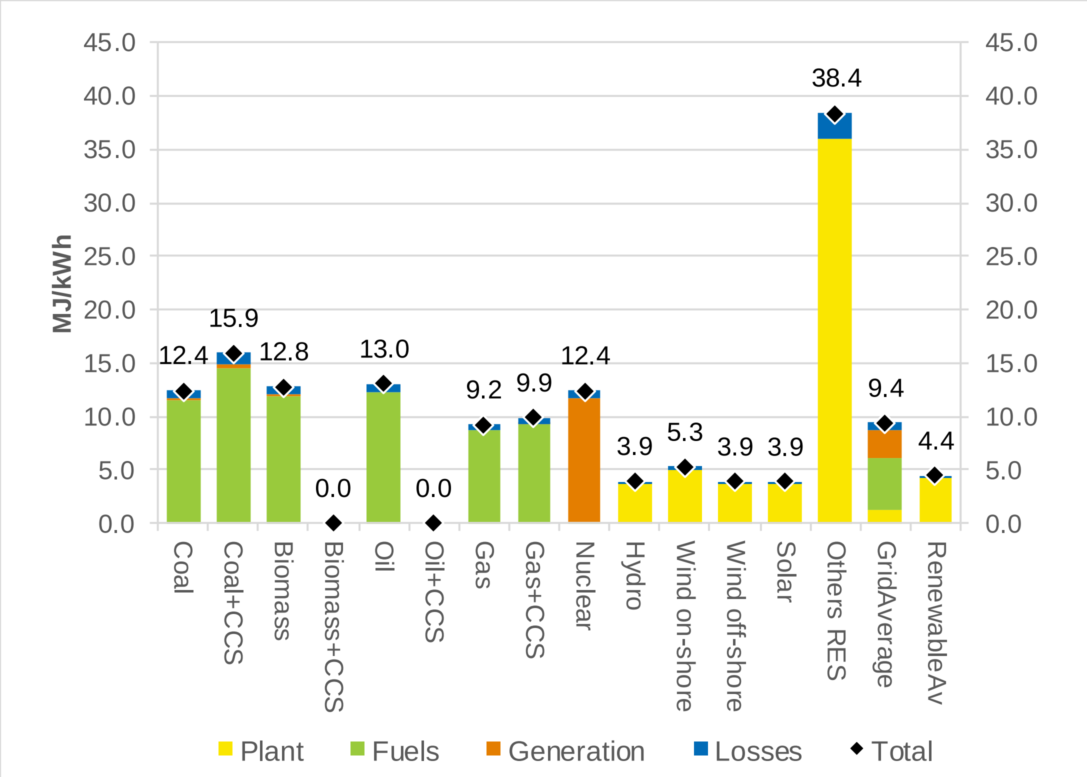
Additional results on the breakdown of different components for other LCA impacts for different electricity chains is provided below, for further context for the discussion provided in the main report Section 5.2.1.

Figure A64: GWP of different electricity generation technologies in the EU28, Tech1.5 scenario 2050



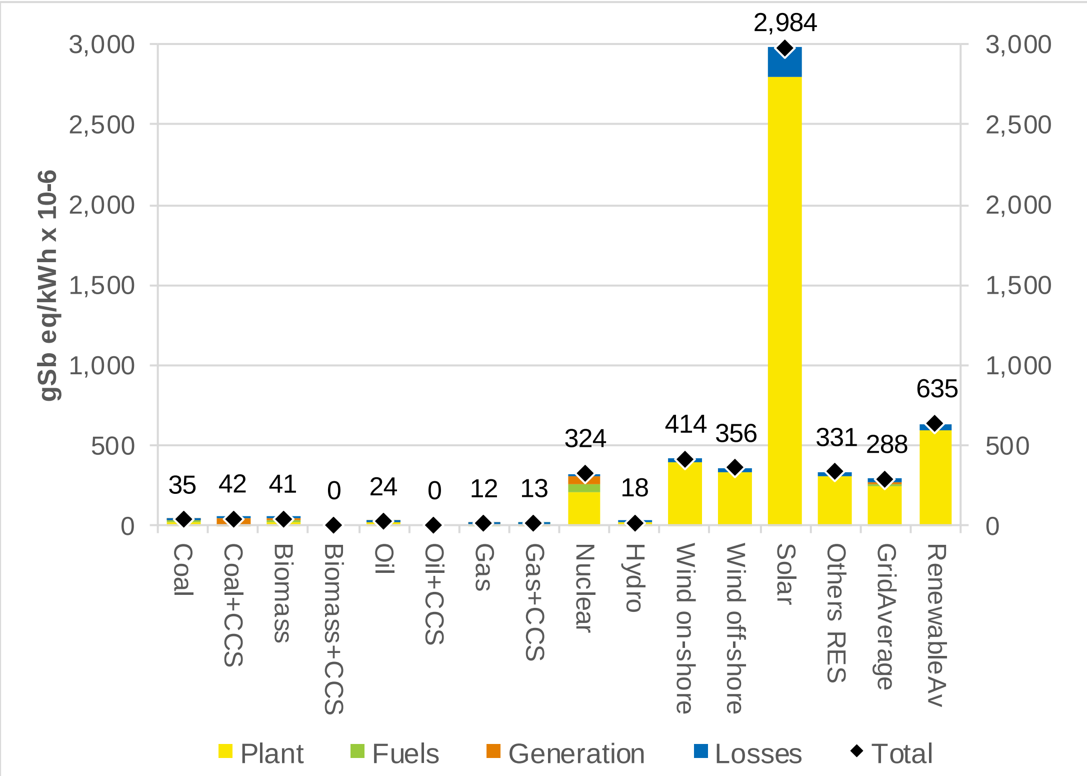
Notes: Plant = Capital Goods: Provision of Infrastrucutre; Fuels = Electricity Fuels: Provision of fuels to generate electricity (e.g. coal, gas, biomass, etc.); Generation: Emissions related to the power plant process itself, meaning direct emissions from the power plant (e.g. exhaust fuems of a coal-fired power plant); Losses = Transmission and Distribution: The emissions derived from efficiency losses due to transmission (regional, international) and distribution (local) of electricity; Total: The sum of all stages. RenewableAv = includes only intermittent renewables (i.e. excludes biomass generation technologies).

Figure A65: CED of different electricity generation technologies in the EU28, Baseline scenario 2020



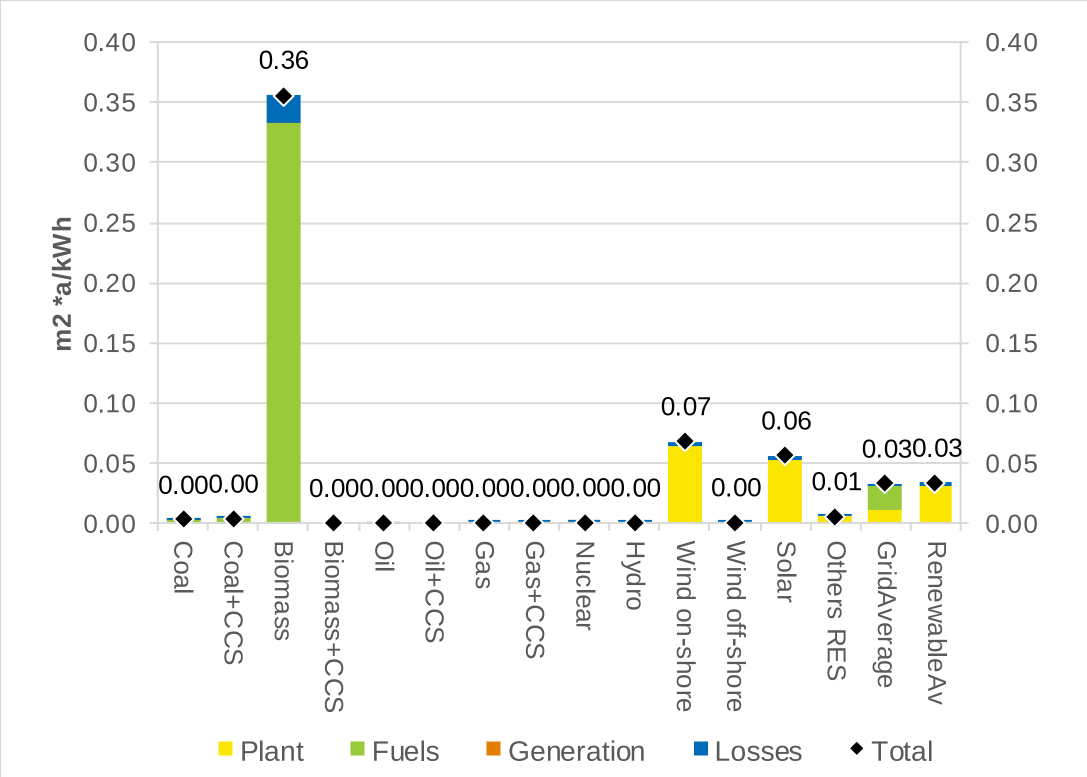
Notes: Values are zero for generation types not utilised in the current scenario/year.

Figure A66: ADP_MM of different electricity generation technologies in the EU28, Baseline scenario 2020



Notes: Values are zero for generation types not utilised in the current scenario/year.

Figure A67: LandU of different electricity generation technologies in the EU28, Baseline scenario 2020



Notes: Values are zero for generation types not utilised in the current scenario/year.

A5.2.2 Additional results for selected Member States

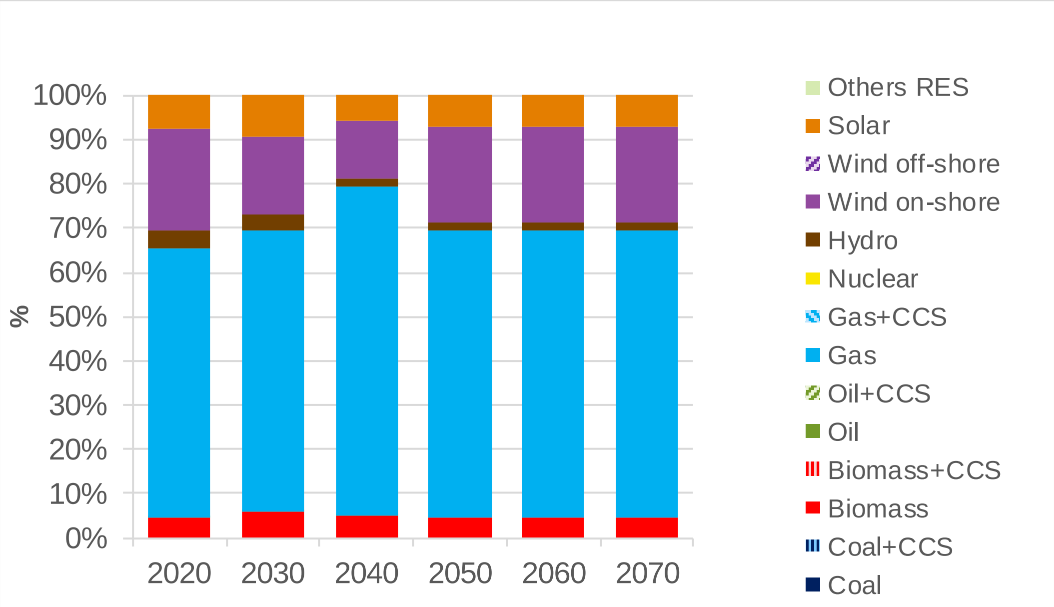
This section provides an in-detail view of the LCA results for key impact categories (GWP, CED, AcidP, EutroP) and four key Member States, Germany, Poland, Sweden and Luxembourg and key impact categories. The former were selected due to their importance in general and for electricity generation in particular (for reference, see Section 3.1.5.2 of the main report). The latter were chosen, because their characteristics represent the different power systems exemplary for the EU28. Regardless of size, whereas Poland and Sweden currently illustrate the differences between a mainly fossil (Poland) and renewable / nuclear (Sweden) power sector, Germany deploys a wide range of different technologies, while Luxembourg's power sector predominantly utilizes gas (approximately 60% - 75%, depending on the year) and a mix of wind power (13% - 22%), solar (5.5% - 9%) and biomass (4.6% - 6%).

The methodology applied (including the use of EU modelling data for two scenarios) is summarised in the main report, and described in more detail in Appendix Section A3.6.2.

A5.2.2.1 Composition and characteristics of the electricity mix of the selected Member States

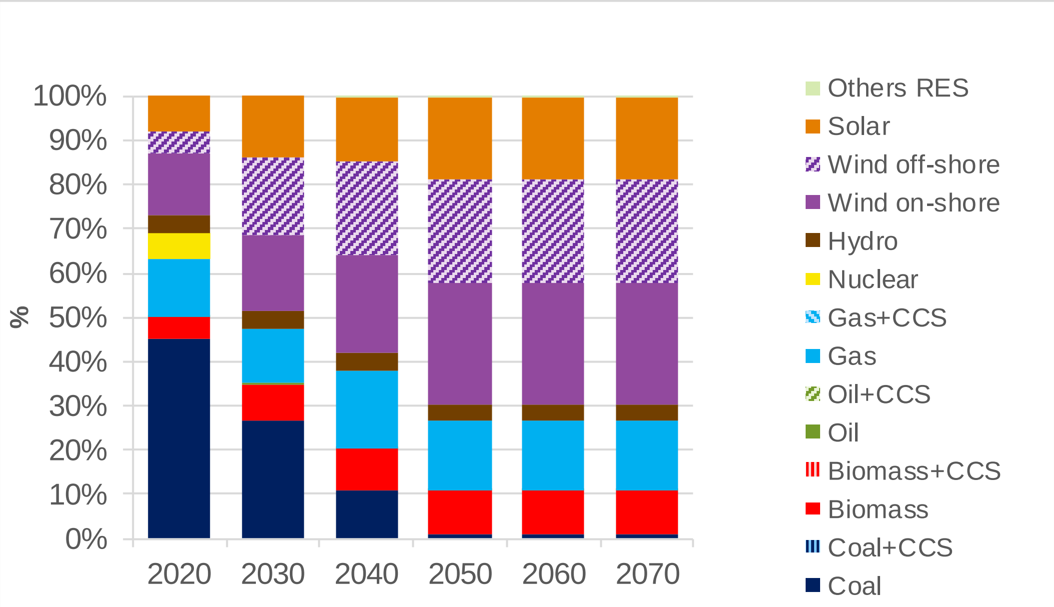
As mentioned above, the four selected Member States are very heterogeneous in their power sector composition. Due to its' location and limited space, Luxembourg only achieves approximately 1/3rd renewables, while the rest remains a more centralized gas power infrastructure.

Figure A68: Power sector composition of Luxembourg, Baseline scenario



In contrast, Germany's power sector transitions rapidly from fossil and nuclear power (combined about 55%) in 2020 towards a phase out of both nuclear and coal power. In 2050, a fossil rest capacity of about 15% (gas power) remains[54].

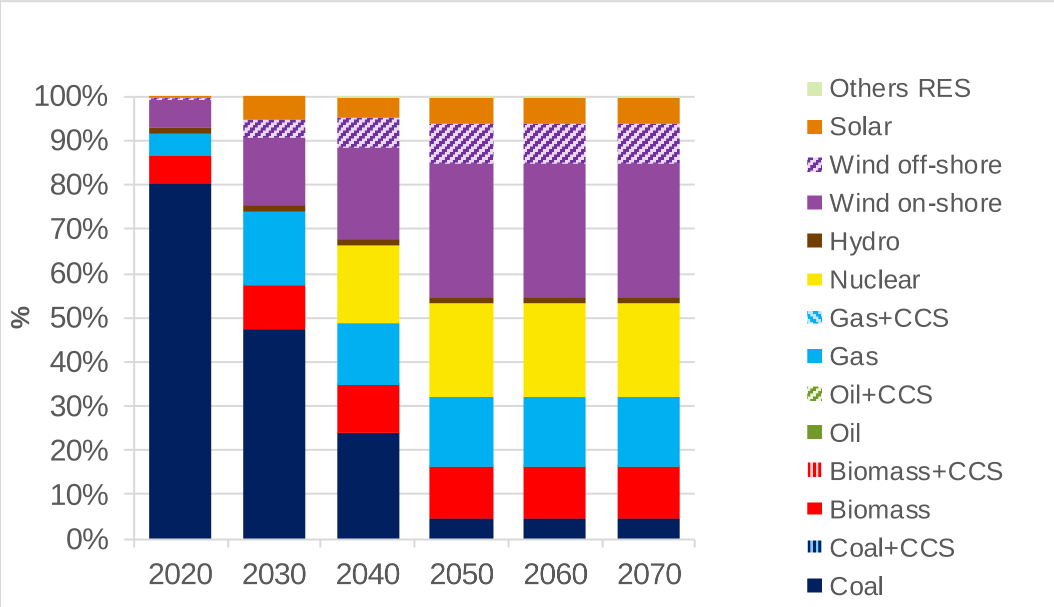
Figure A69: Power sector composition of Germany, Baseline scenario



Poland, on the other hand, currently relies heavily on coal power (80%). Though a change is envisioned, too, for Poland, the focus remains on conventional power generation, utilizing a mix of nuclear, gas and coal which adds up to approximately 40% in 2050.

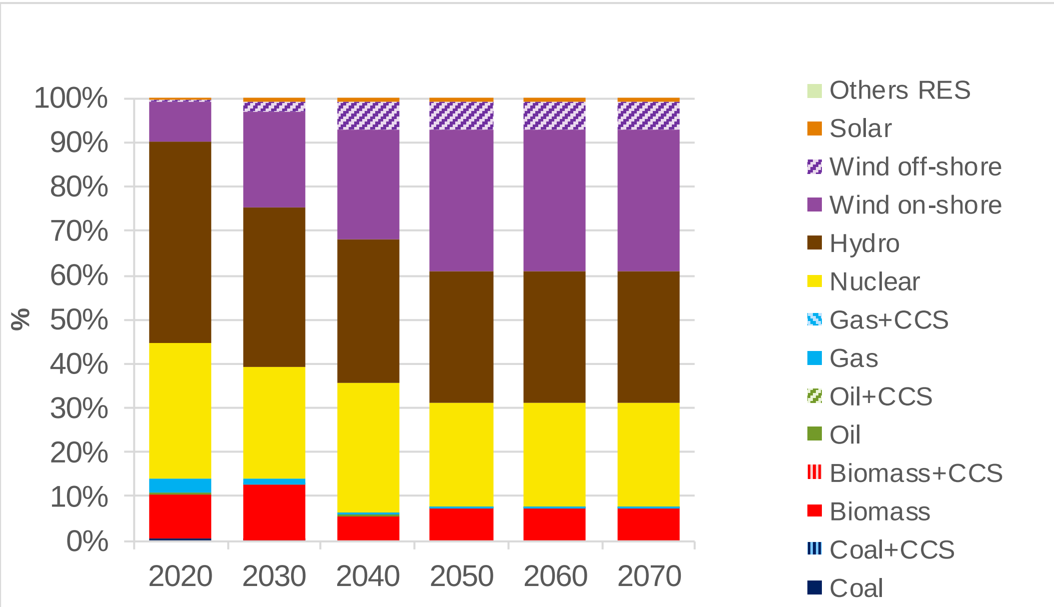
[54] Considering the current development in electricity generation in Europe and Germany in particular, 15% fossil power generation constitutes a rather conservative estimation, even for the Baseline scenario.

Figure A70: Power sector composition of Poland, Baseline scenario



The vast majority of power generation in Sweden currently comes from different renewables, mostly hydro. The conversion of Sweden's power sector following the EC PRIMES model will see a decrease of hydro, nuclear and, to a lesser extent, biomass and an increase in wind power, both onshore and offshore.

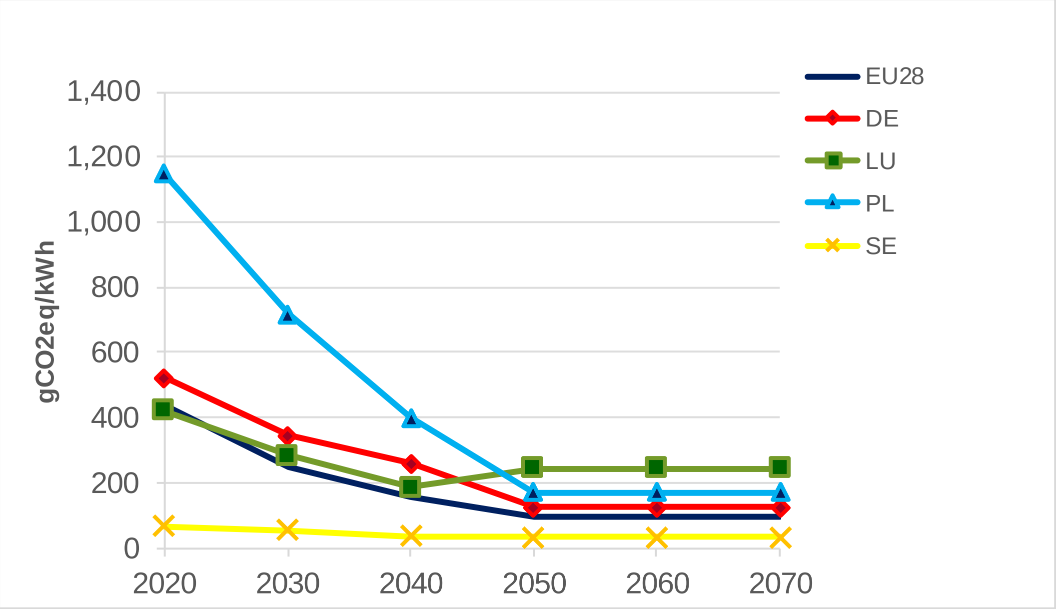
Figure A71: Power sector composition of Sweden, Baseline Scenario



A5.2.2.2 Additional Member State LCA results for Climate Change (GWP)

While the change over time is most visible in Poland, the GWP of Sweden develops only slightly, but nevertheless constitutes the best performing Member State. Quantitatively, the results in the impact category GWP range from 1.150 g CO_2eq/kWh (Poland, 2020) to 34 g CO_2eq/kWh (Sweden 2050). The rise in GWP in Luxembourg in 2050 compared to 2040 is due to the increase in gas-fired power generation.

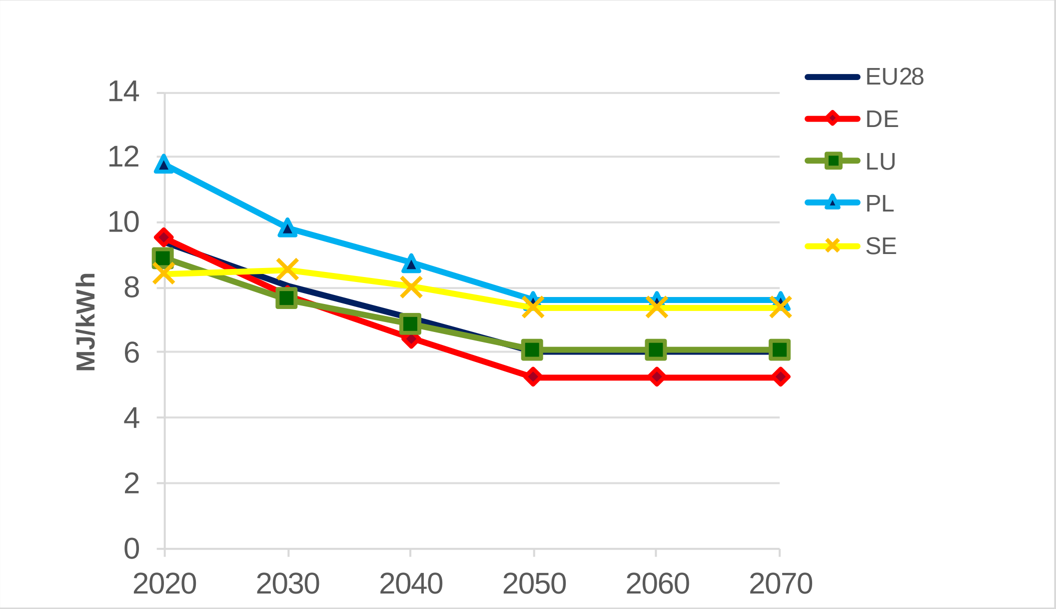
Figure A72: GWP of selected Member States compared to the EU28 average, Baseline scenario



A5.2.2.3 Additional Member State LCA results for Cumulated Energy Demand (CED)

Renewables (except biomass) on average result in a lower CED when compared to fossil and especially nuclear power generation. This is visible in the results for both Poland and Sweden, especially compared to Luxembourg with a higher share of fossils[55]. Figure A73 provides an overview with results ranging from 11.8 MJ/kWh (Poland, 2020) to 5.2 MJ/kWh (Germany, 2050).

Figure A73: CED of selected Member States and the EU28, Baseline scenario

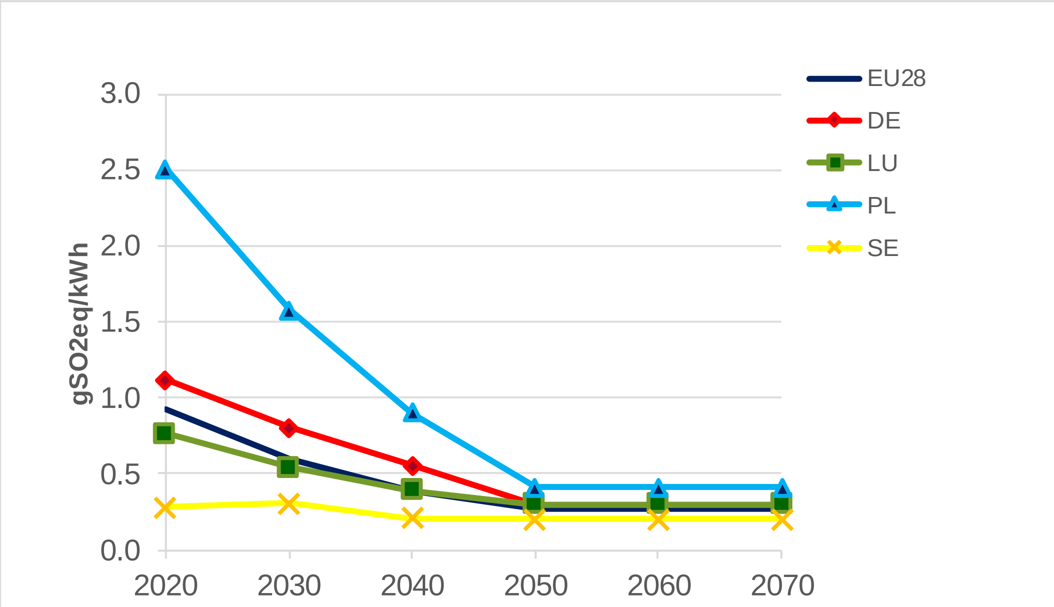


[55] The CED is reciprocally equivalent to the efficiency of the conversion of fuel to power. Gas power comparatively achieve high efficiencies when matched with nuclear or coal power plants.

A5.2.2.4 Additional Member State LCA results for Acidification Potential (AcidP)

The Acidification Potential for power generation is mostly a function of the sulphur content of the utilized fuel(s)[56] and exhaust gas treatment. As coal contains on average comparatively high sulphur shares, a coal fired power plant will produce more SO_2 than a gas fired power plant, even without taking into account conversion efficiencies. This is illustrated by the stark decline in Poland and Germany, following a phase out of coal, and the significantly lower results for Luxembourg (see Figure A68). Renewables and nuclear result in very low acidification, which can be observed in the low results for Sweden across all investigated years. Results in Europe range from 2.5 g SO_2eq/kWh (Poland, 2020) to 0.2 g SO_2eq/kWh (Sweden, 2050).

Figure A74: Acidification Potential of selected Member States and the EU28, Baseline Scenario

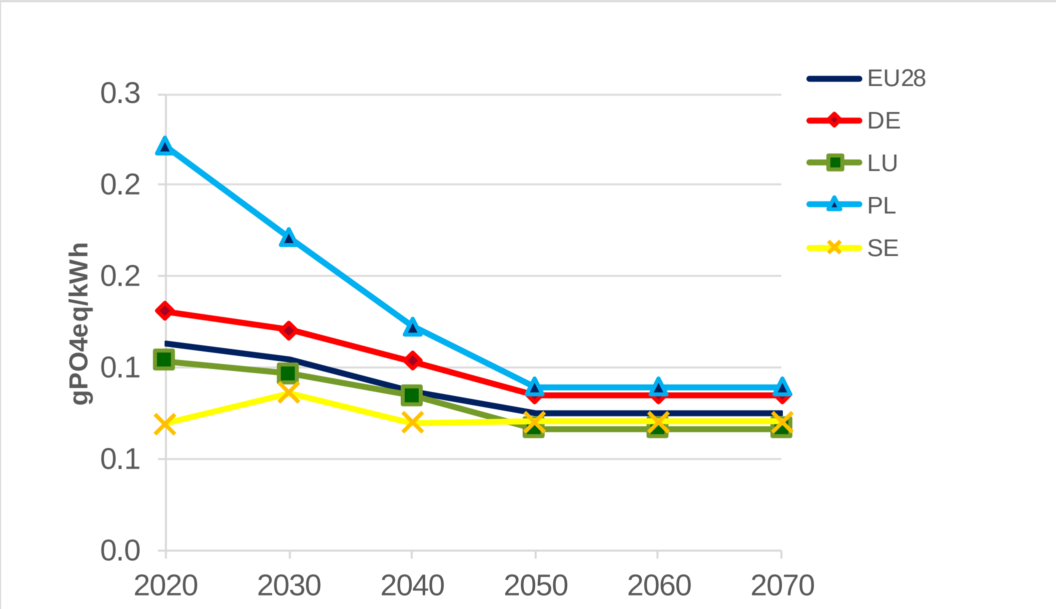


A5.2.2.5 Additional Member State LCA results for Eutrophication Potential (EutroP)

The Eutrophication Potential is mainly influenced by the formation of NO_x, NH_3 as emissions to the air and phosphorous and nitrogenous compounds to water. The former, especially NO_x, is created during combustion processes and is specifically higher for coal when compared with gas power plant[57]. RES and nuclear without combustion thus result in lower eutrophication impacts (see Figure A75).

[56] This holds true for all investigated lifecycle stages, resulting in values greater zero for e.g. nuclear or wind power.
[57] This is due to the fuel and combustion chamber characteristics.

Figure A75: Eutrophication Potential of selected Member States and EU28, Baseline scenario



A5.3 Overall vehicle cycle LCA – Additional results

This section provides additional results for the overall vehicle cycle to supplement the material found in the main body of the report.

A5.3.1 Additional results for lower medium cars

The following charts provide a detailed breakdown by powertrain of the other LCA impacts; a summary of the key trends present in the charts provided below is provided in the main report in Section 5.4.1.2.

Figure A76: Summary of breakdown of overall lifecycle CED impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

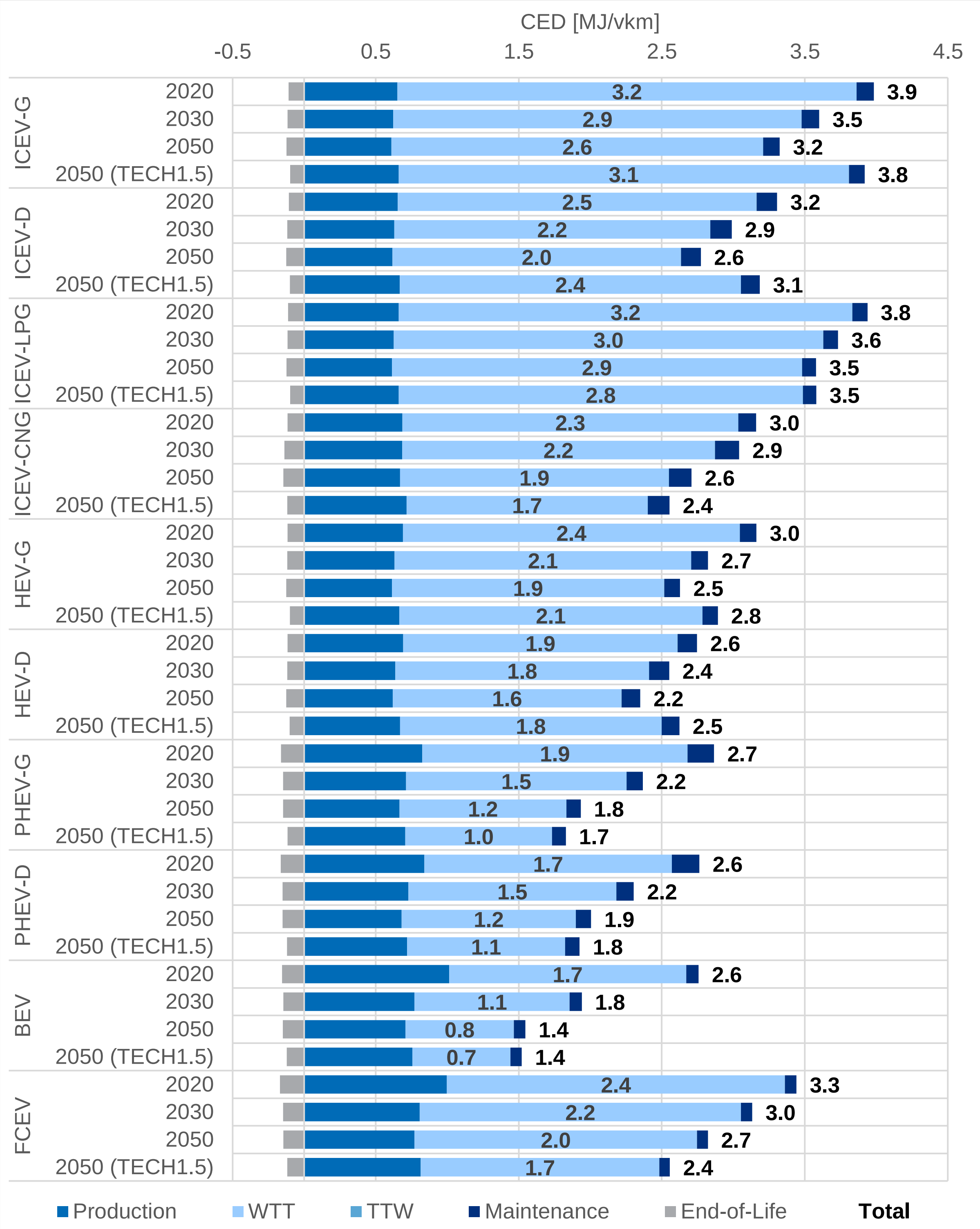


Figure A77: Summary of breakdown of overall lifecycle POCP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

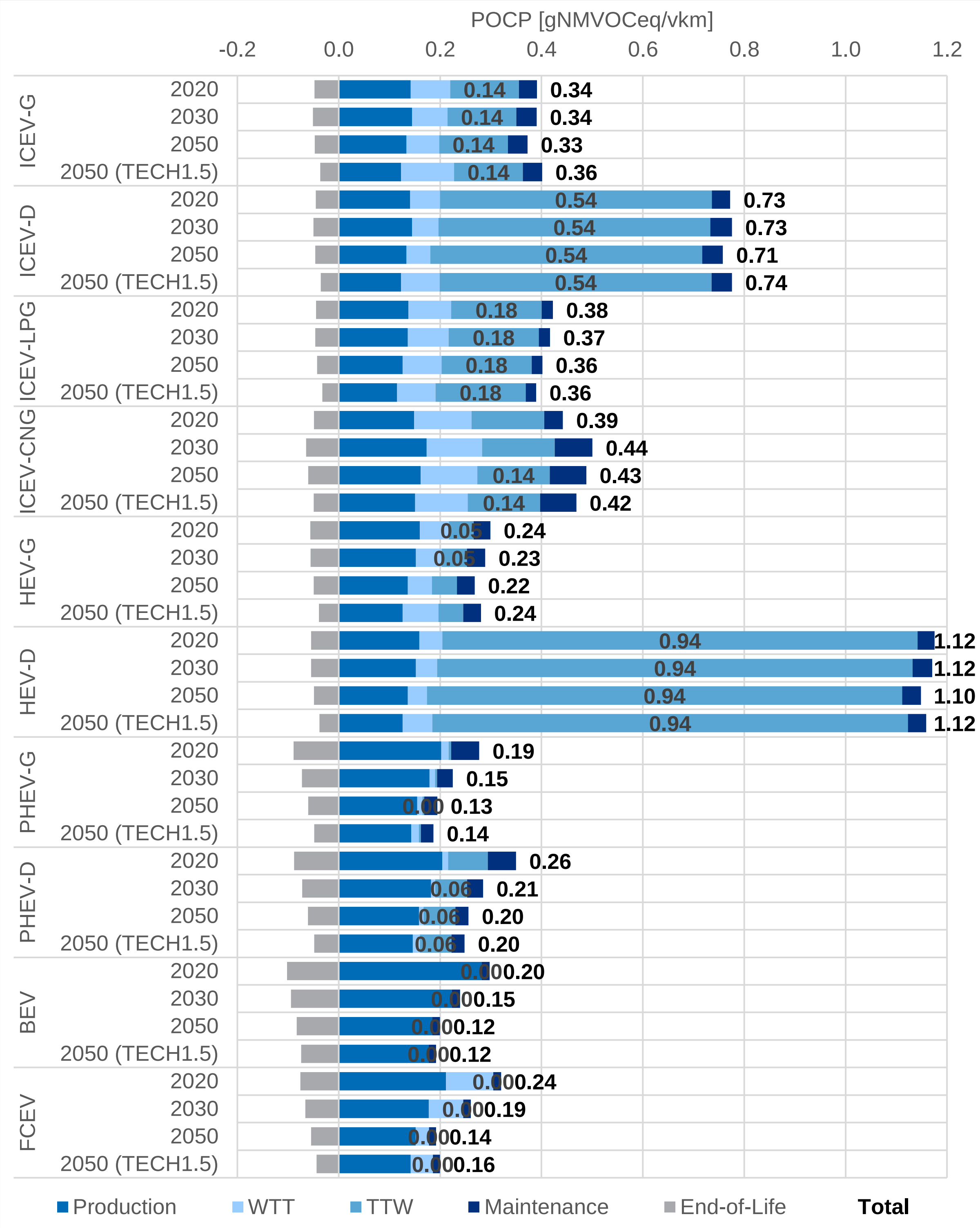


Figure A78: Summary of breakdown of overall lifecycle PMF impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

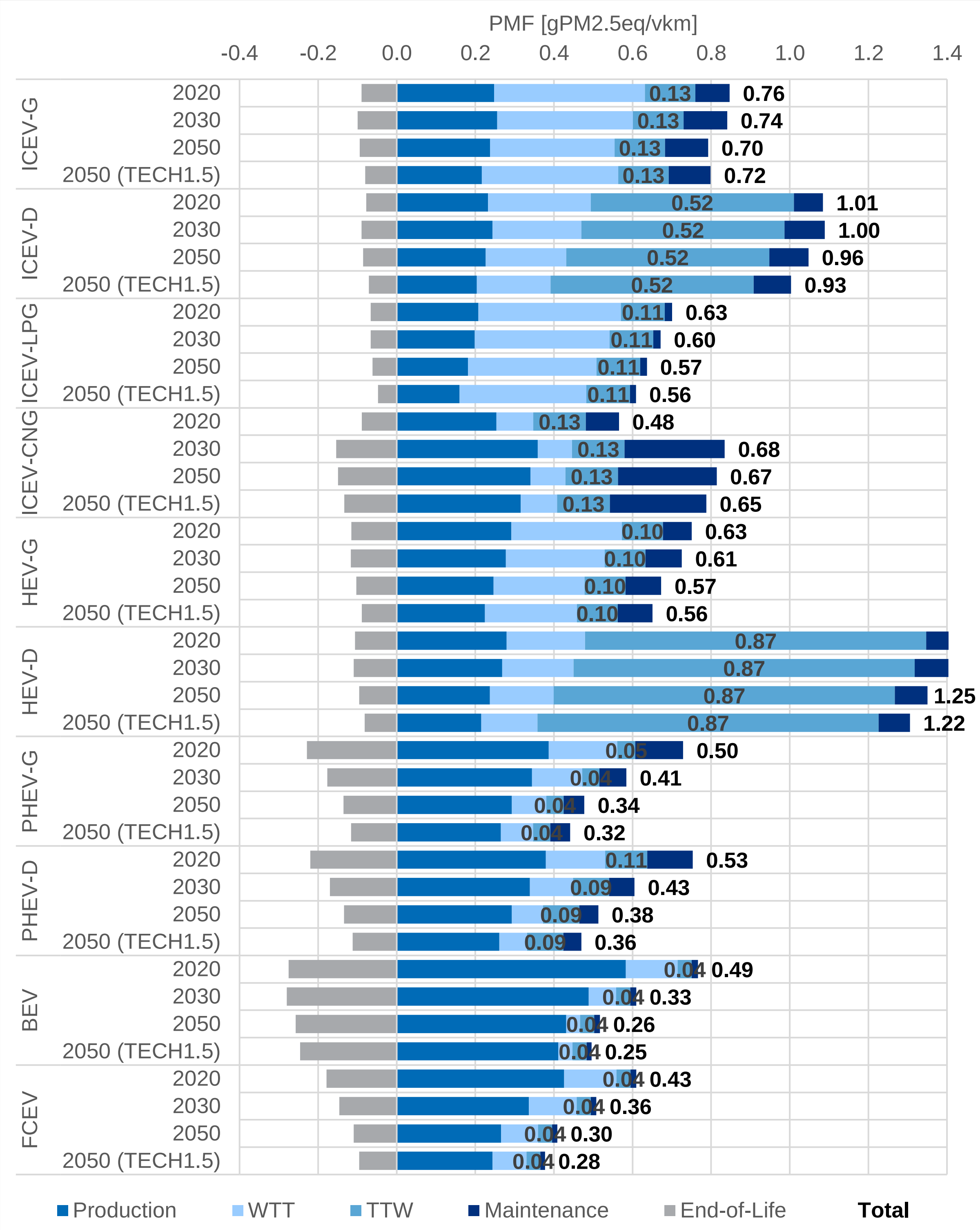


Figure A79: Summary of breakdown of overall lifecycle HTP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

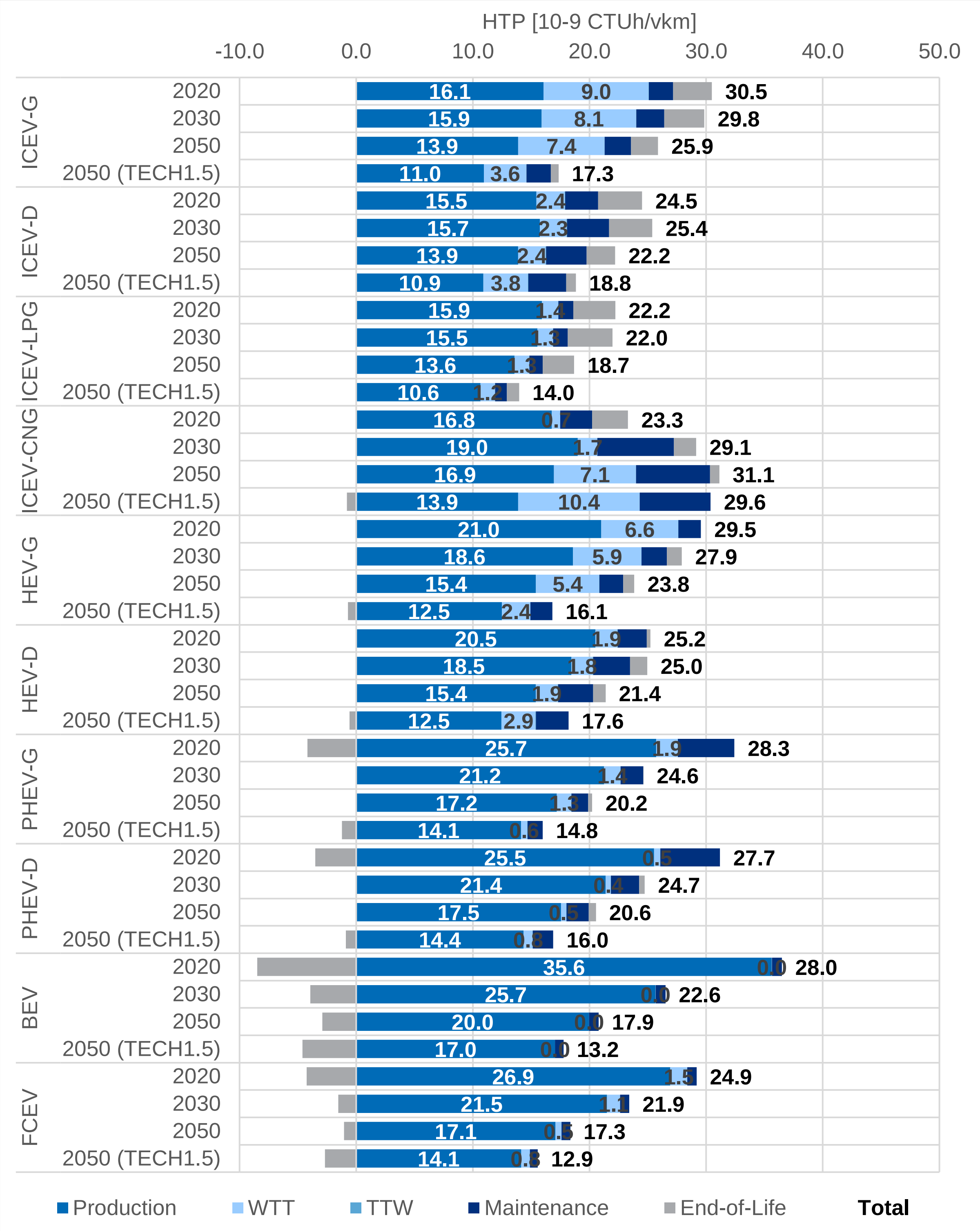


Figure A80: Summary of breakdown of overall lifecycle ADP_MM impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

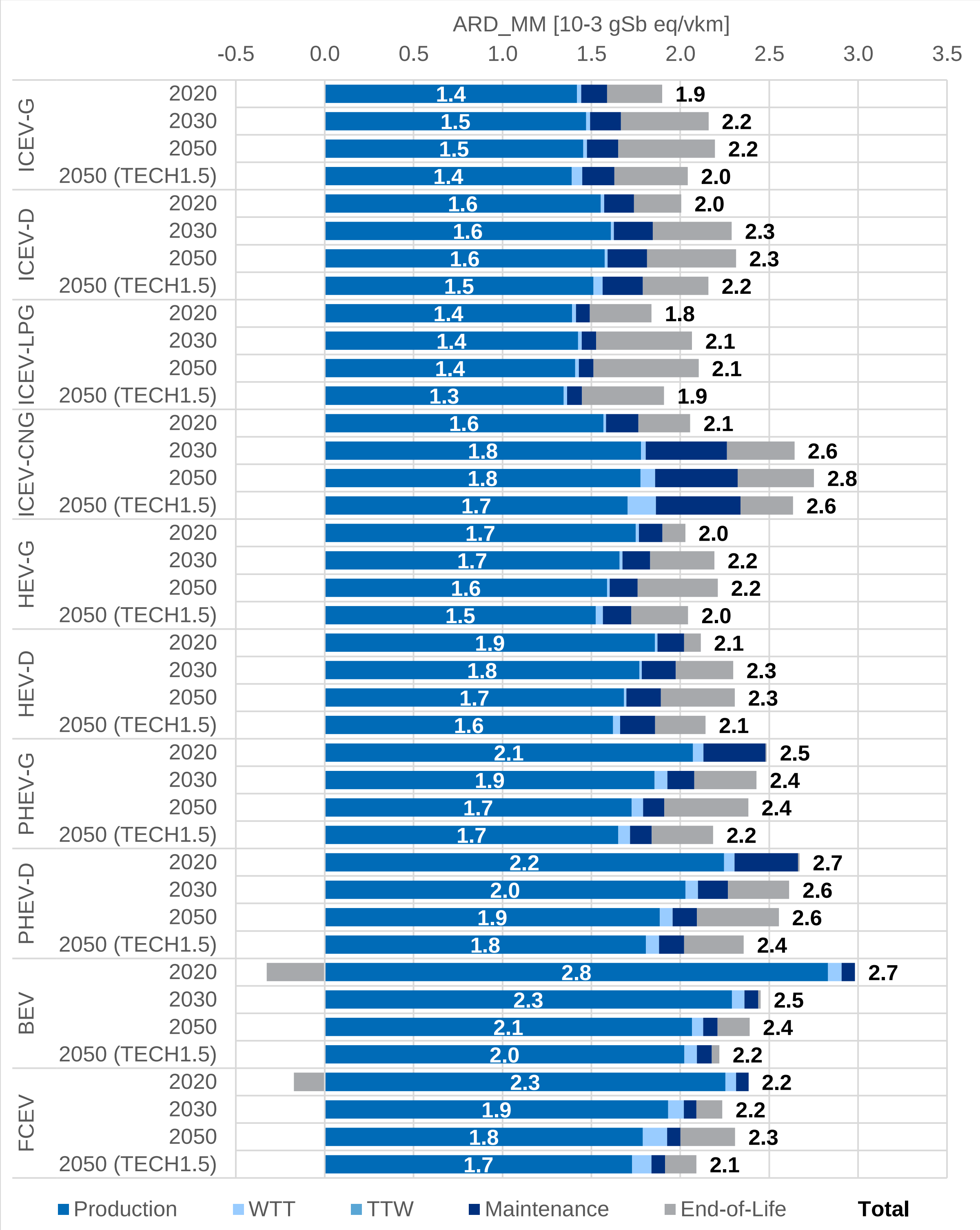


Figure A81: Summary of breakdown of overall lifecycle WaterS impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)

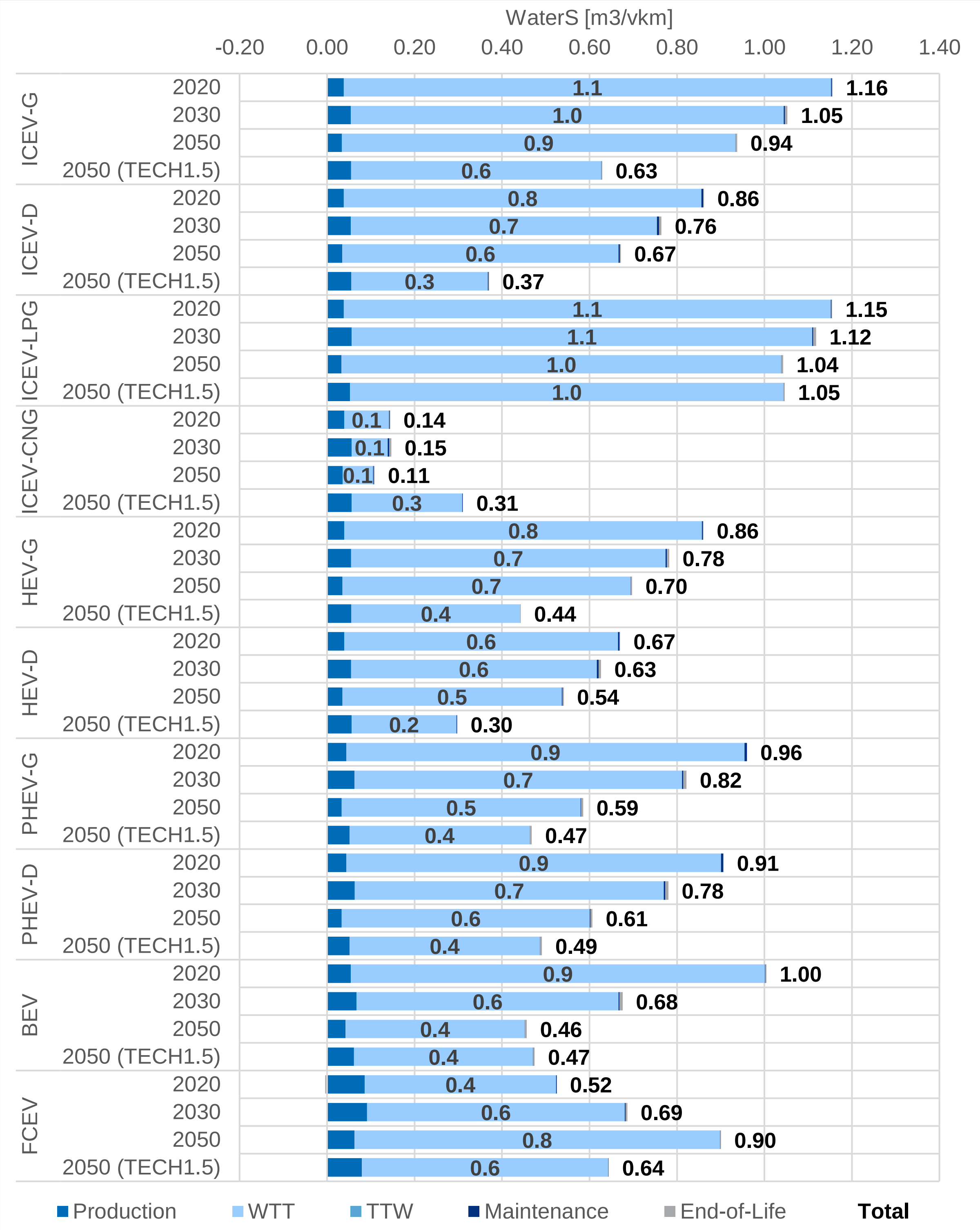


Figure A82: Summary of breakdown of overall lifecycle AcidP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

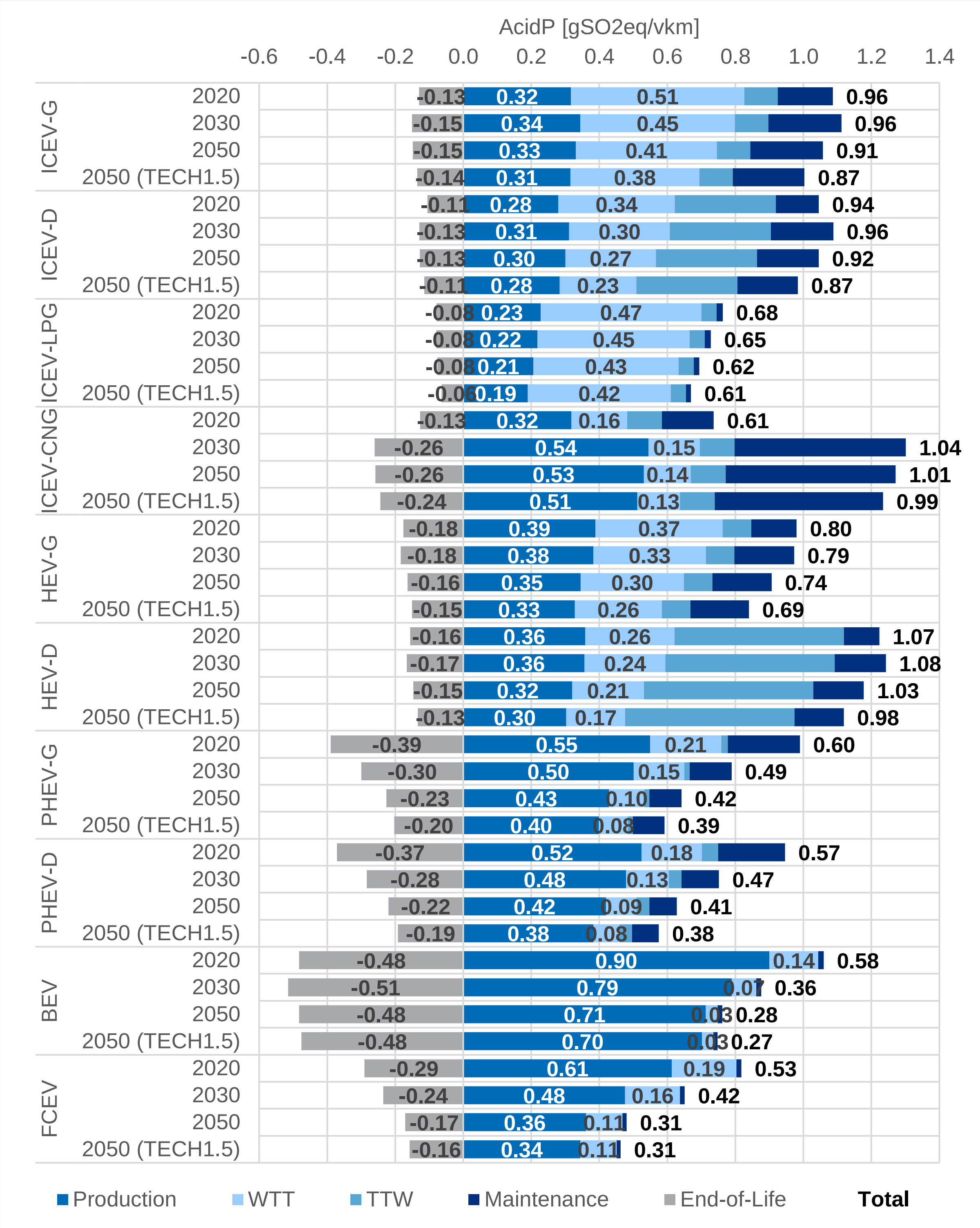


Figure A83: Summary of breakdown of overall lifecycle EutroP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

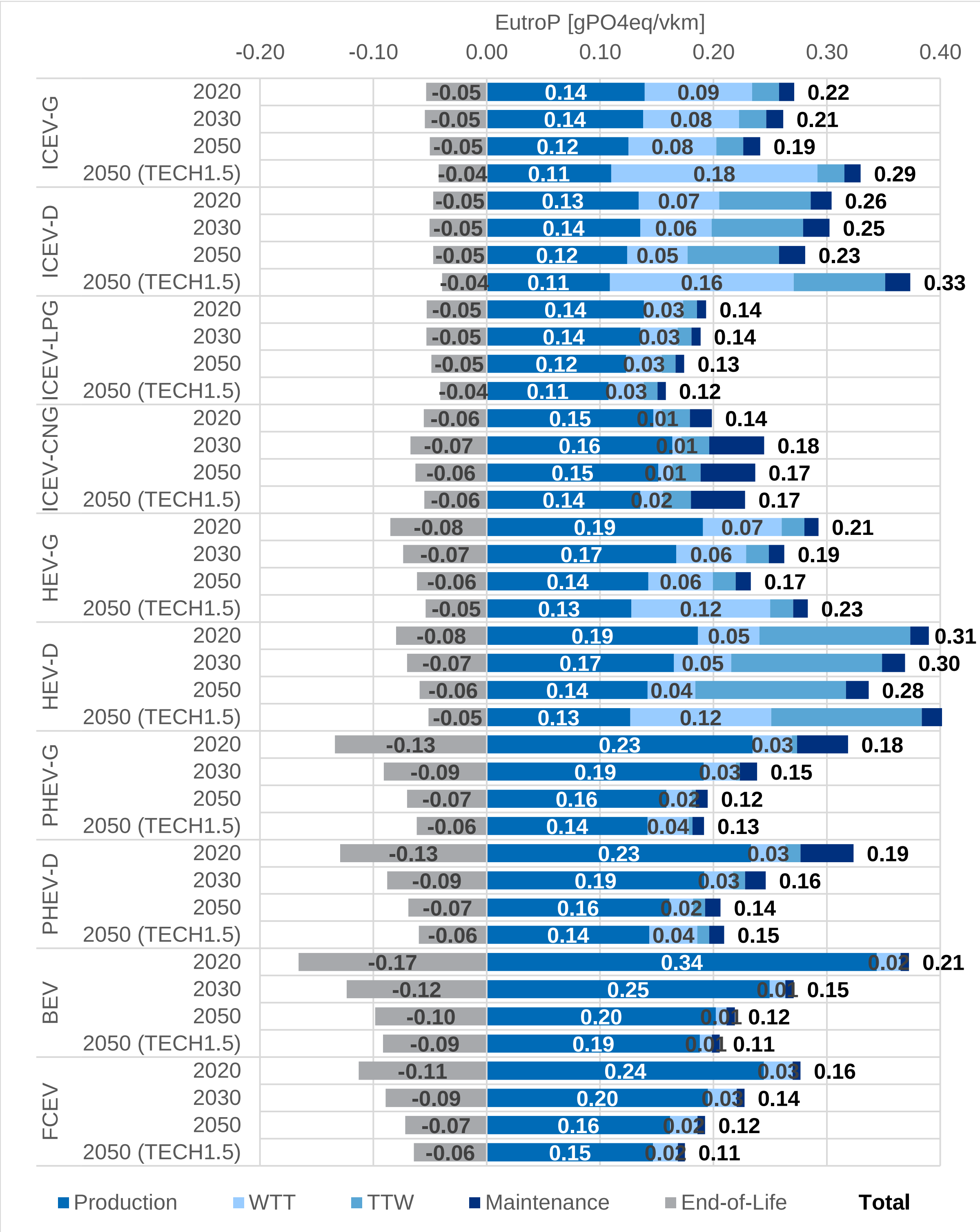


Figure A84: Summary of breakdown of overall lifecycle ODP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

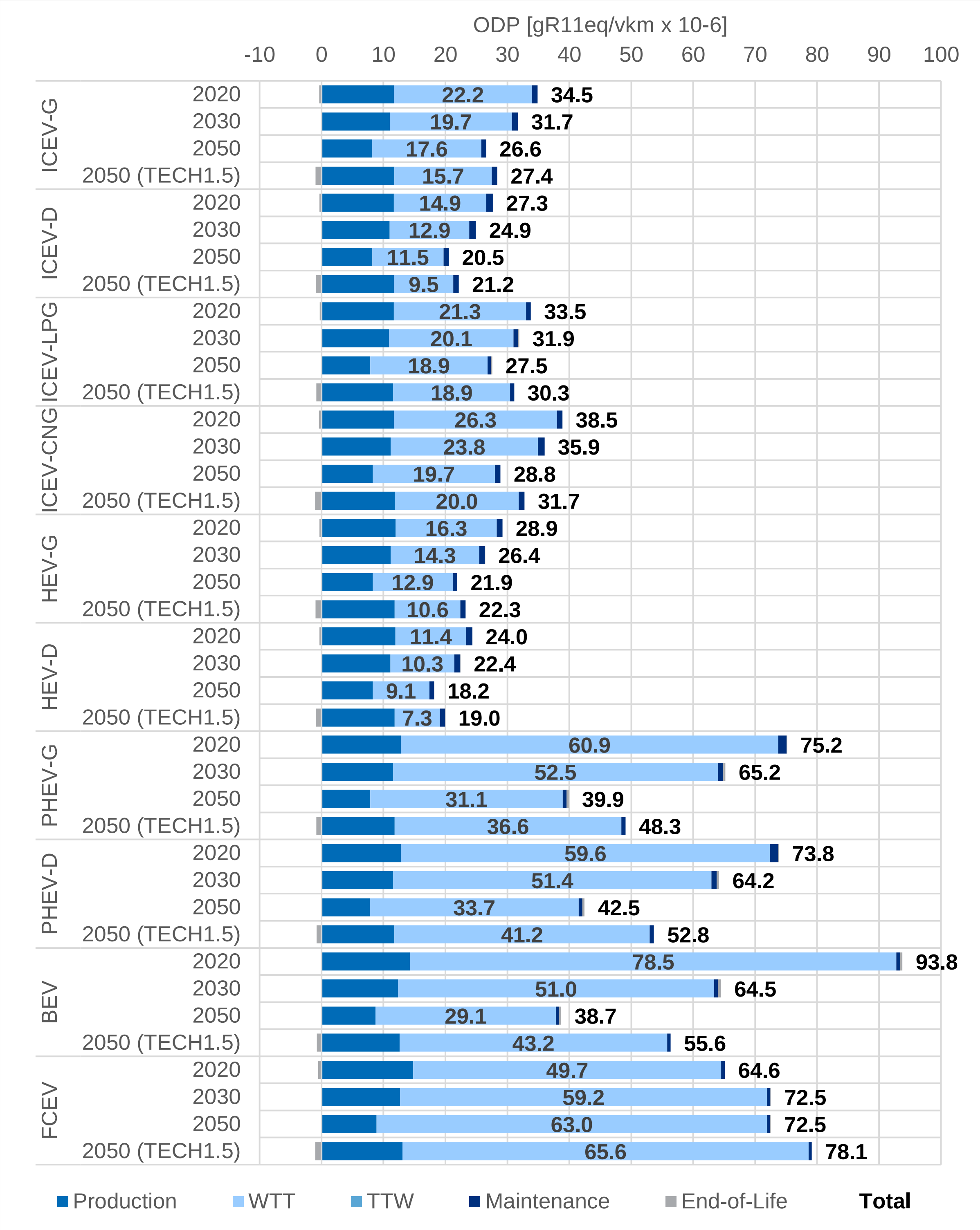


Figure A85: Summary of breakdown of overall lifecycle ETP_FA impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

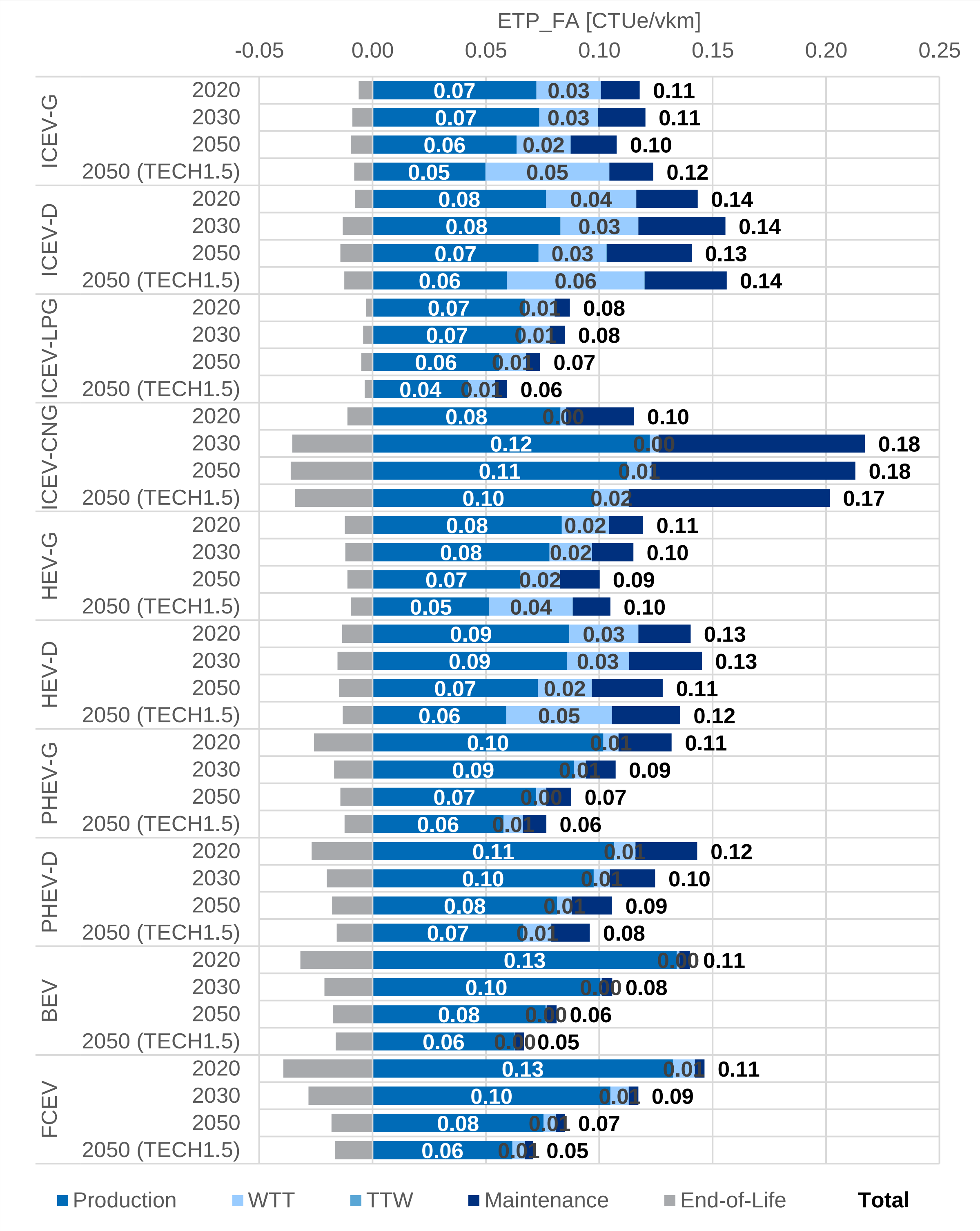


Figure A86: Summary of breakdown of overall lifecycle ARD_FE impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

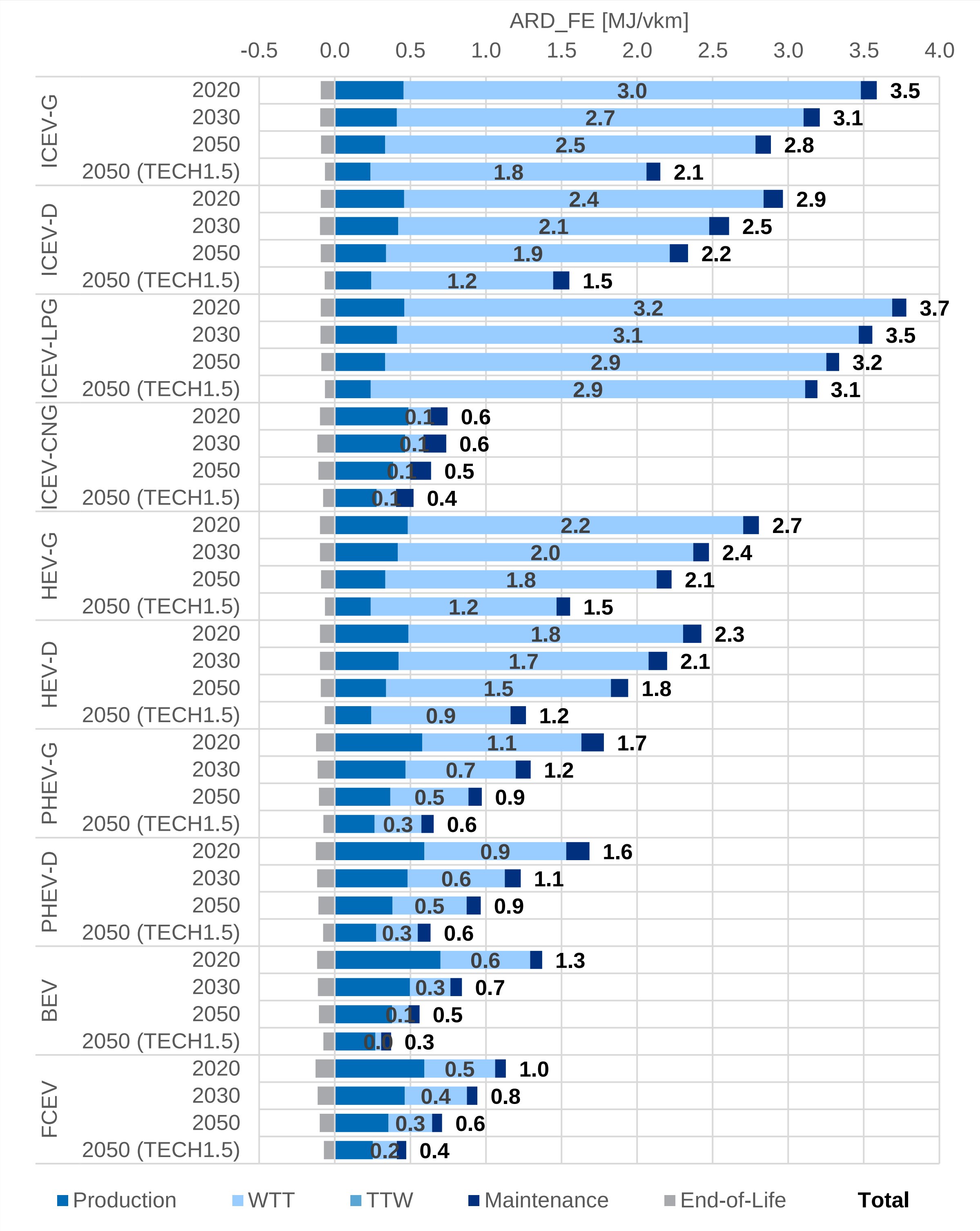


Figure A87: Summary of breakdown of overall lifecycle LandU impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

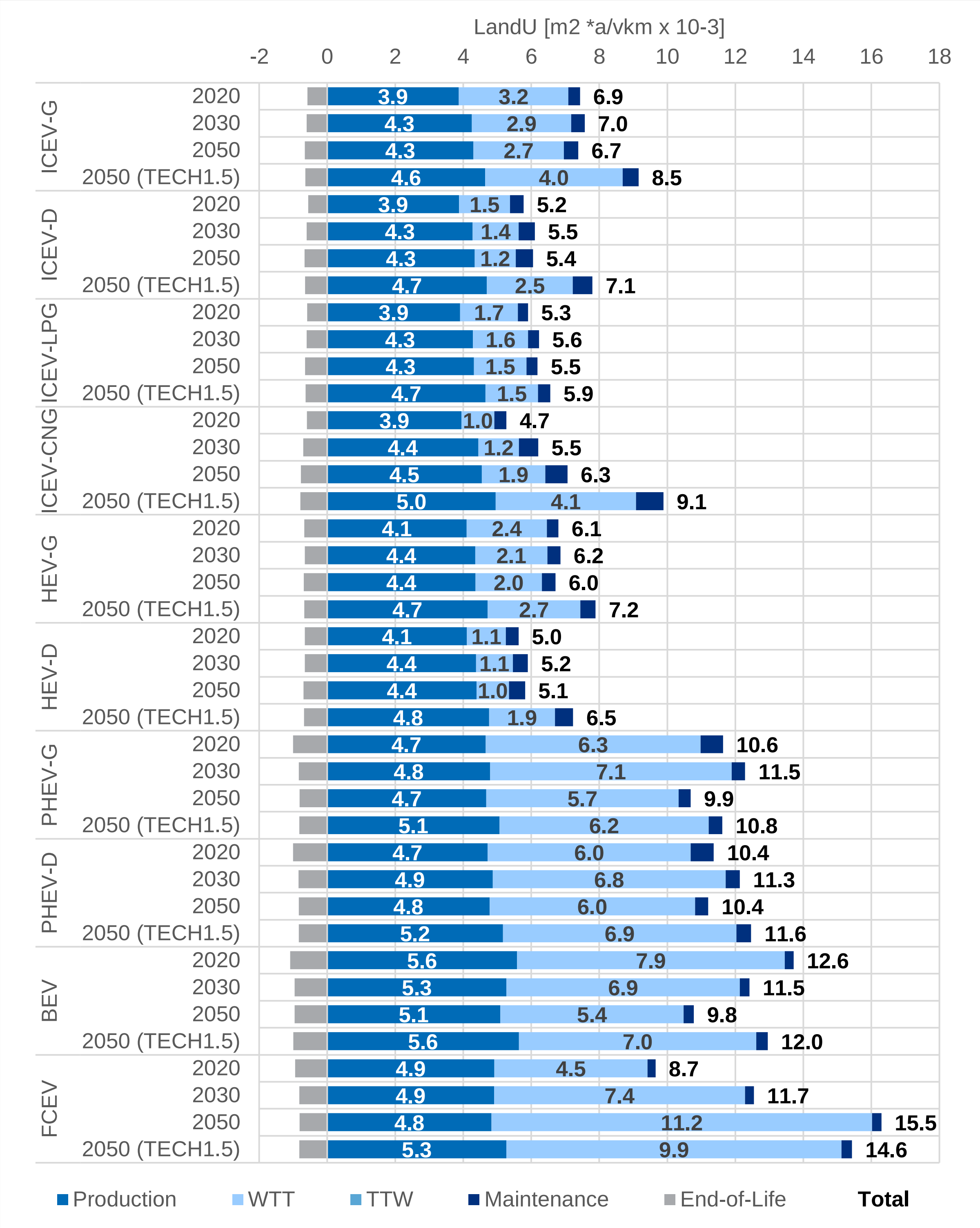


Figure A88: Summary of breakdown of overall lifecycle IRP impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)

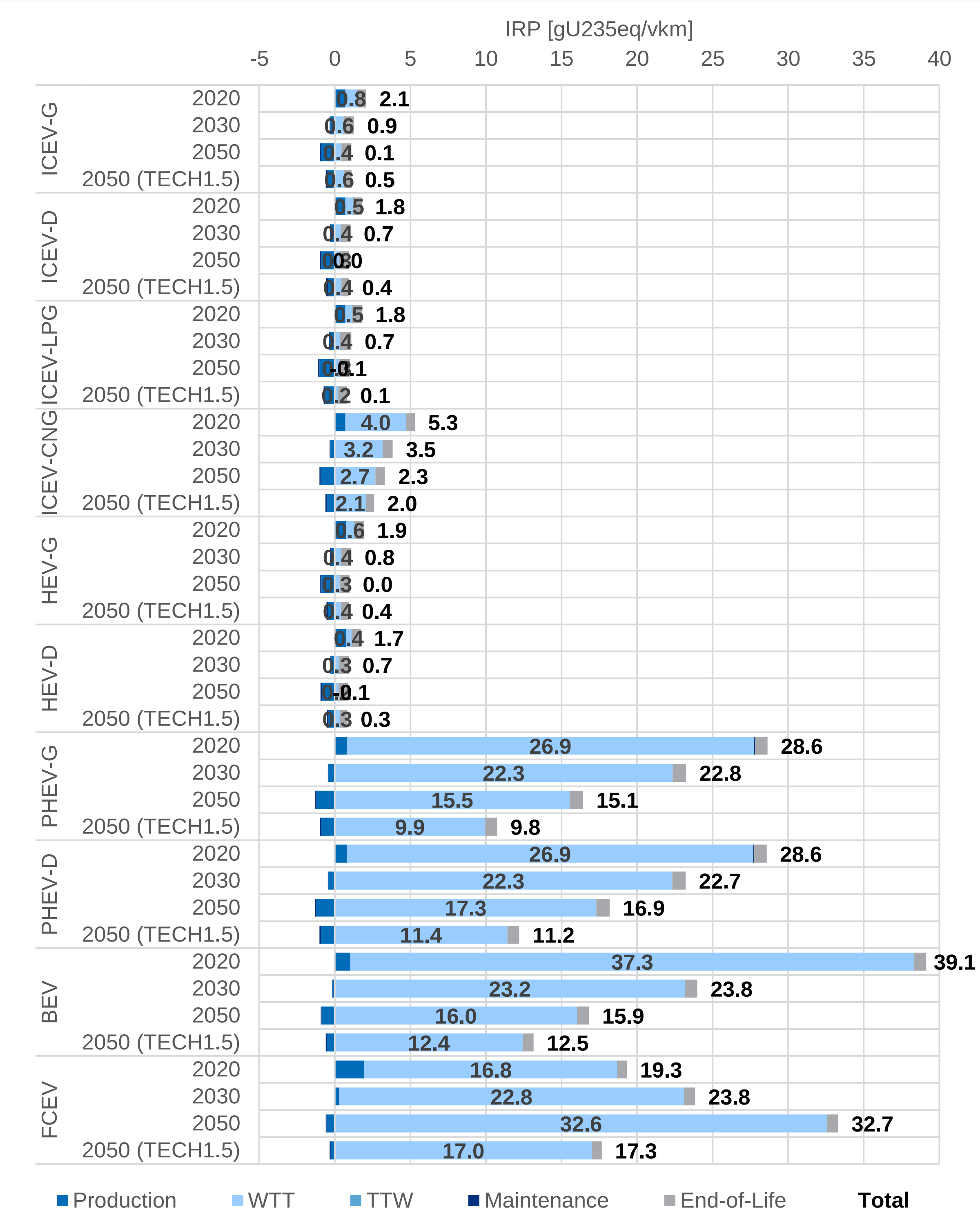
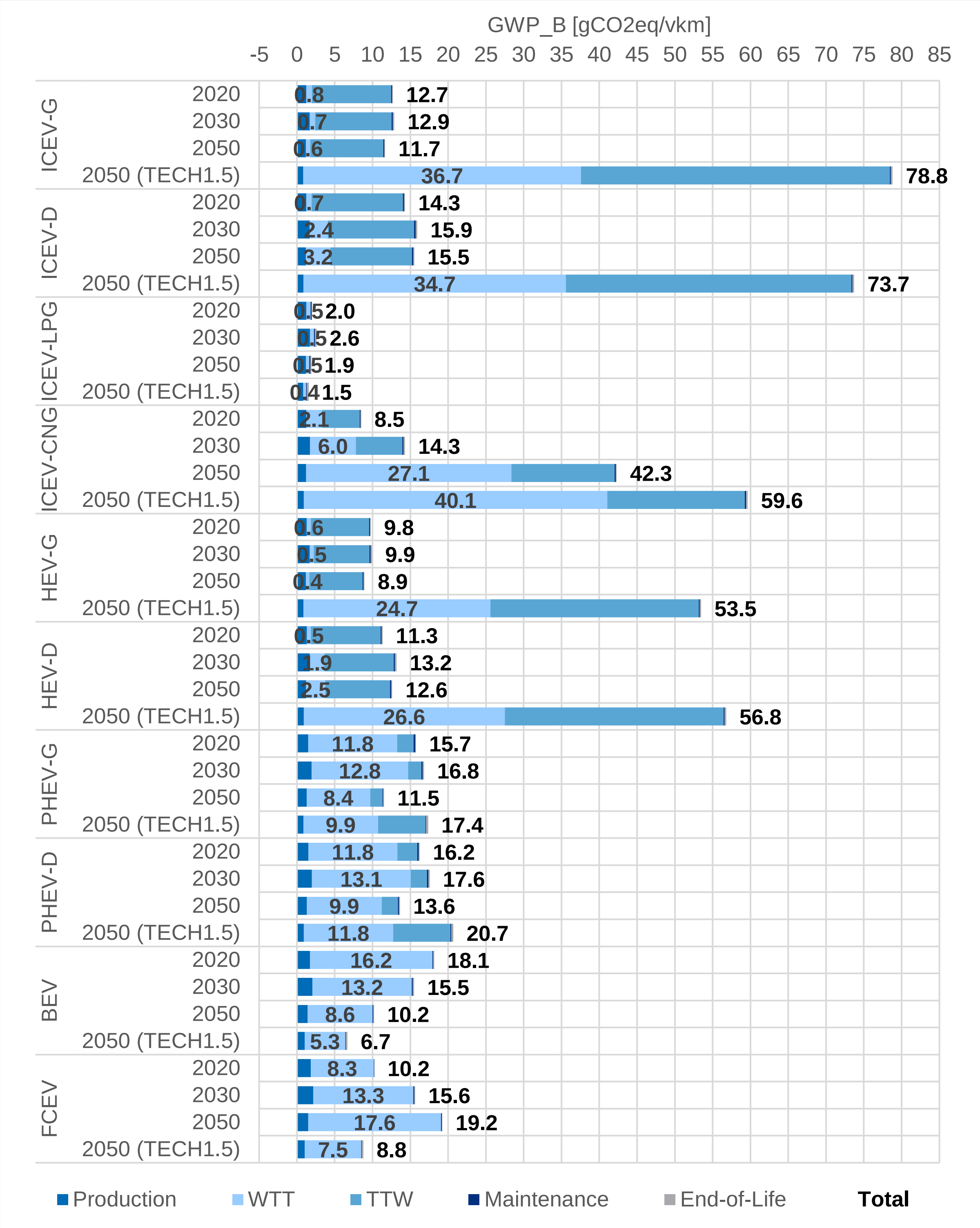


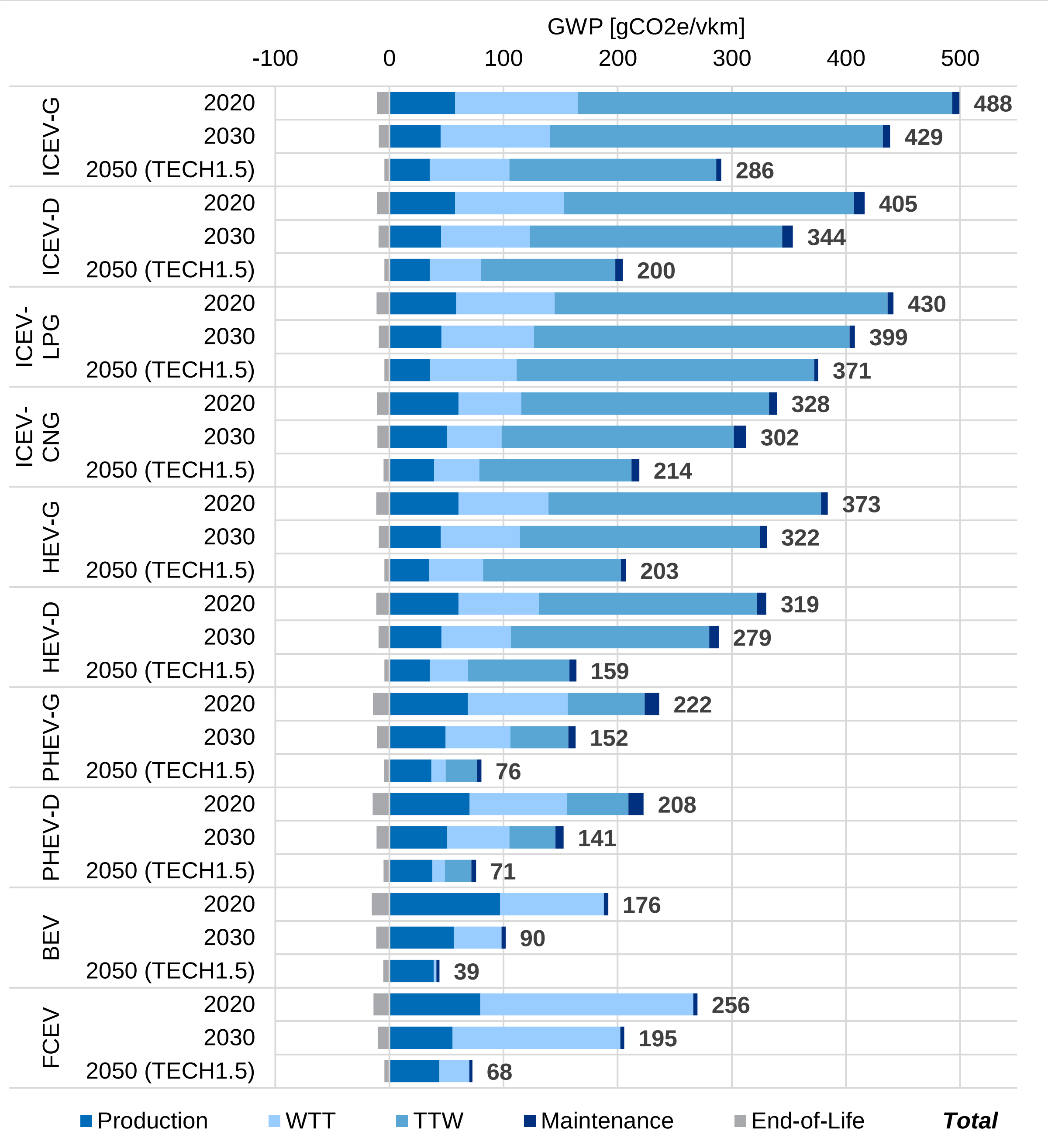
Figure A89: Summary of breakdown of overall lifecycle GWP_B impacts for Lower Medium Cars for different powertrain types (Baseline scenario for 2020 and 2050)



A5.3.2 Additional results for other vehicle types

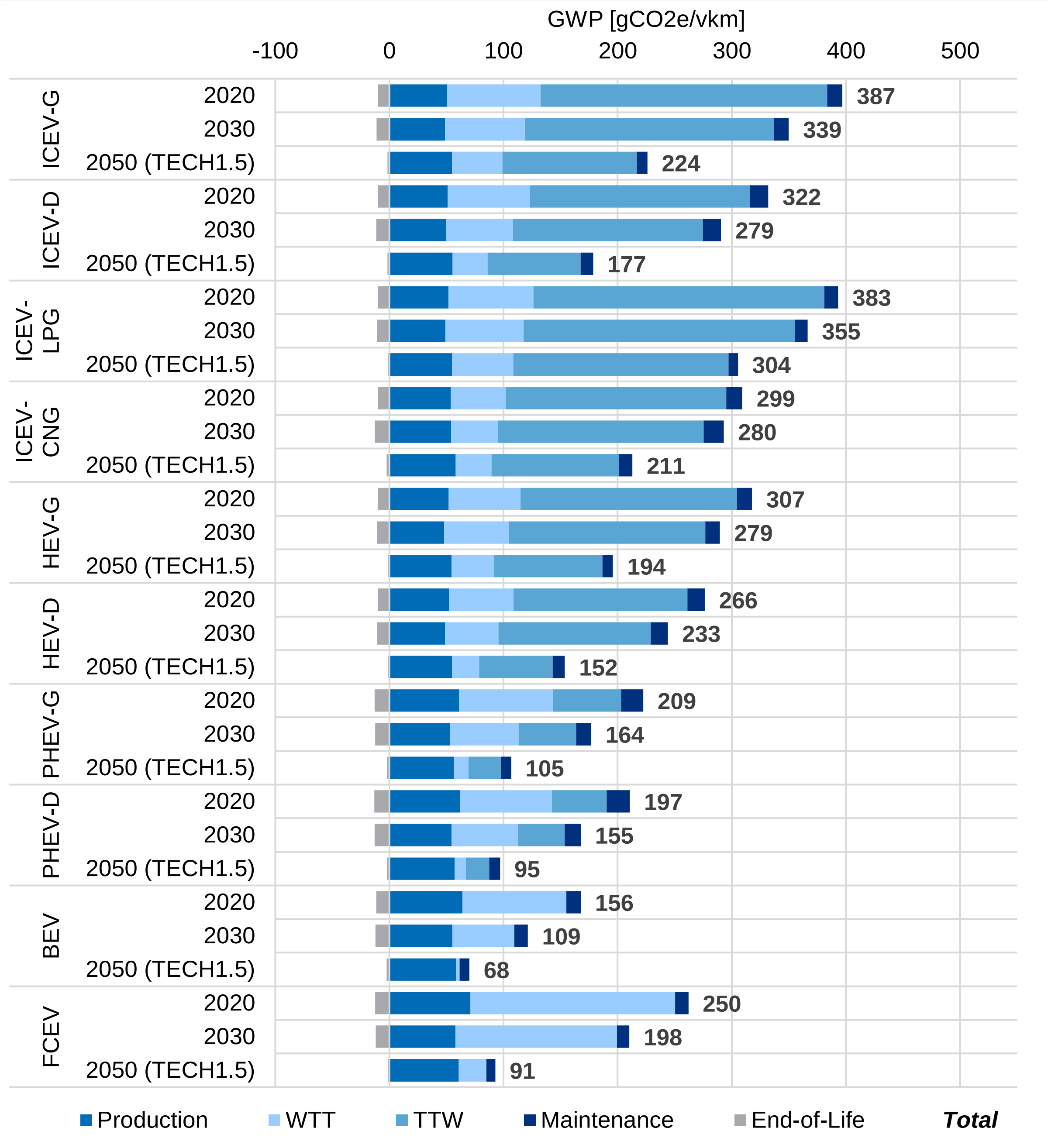
The following figures provide a summary of results for the other vehicle types (large SUV passenger cars, N1 Class III vans and coaches) that were not included in the main body of the report. The results presented here broadly show similar trends as those already shown for the other vehicle types.

Figure A90: Summary of breakdown of overall lifecycle GWP impacts for large SUV passenger cars for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



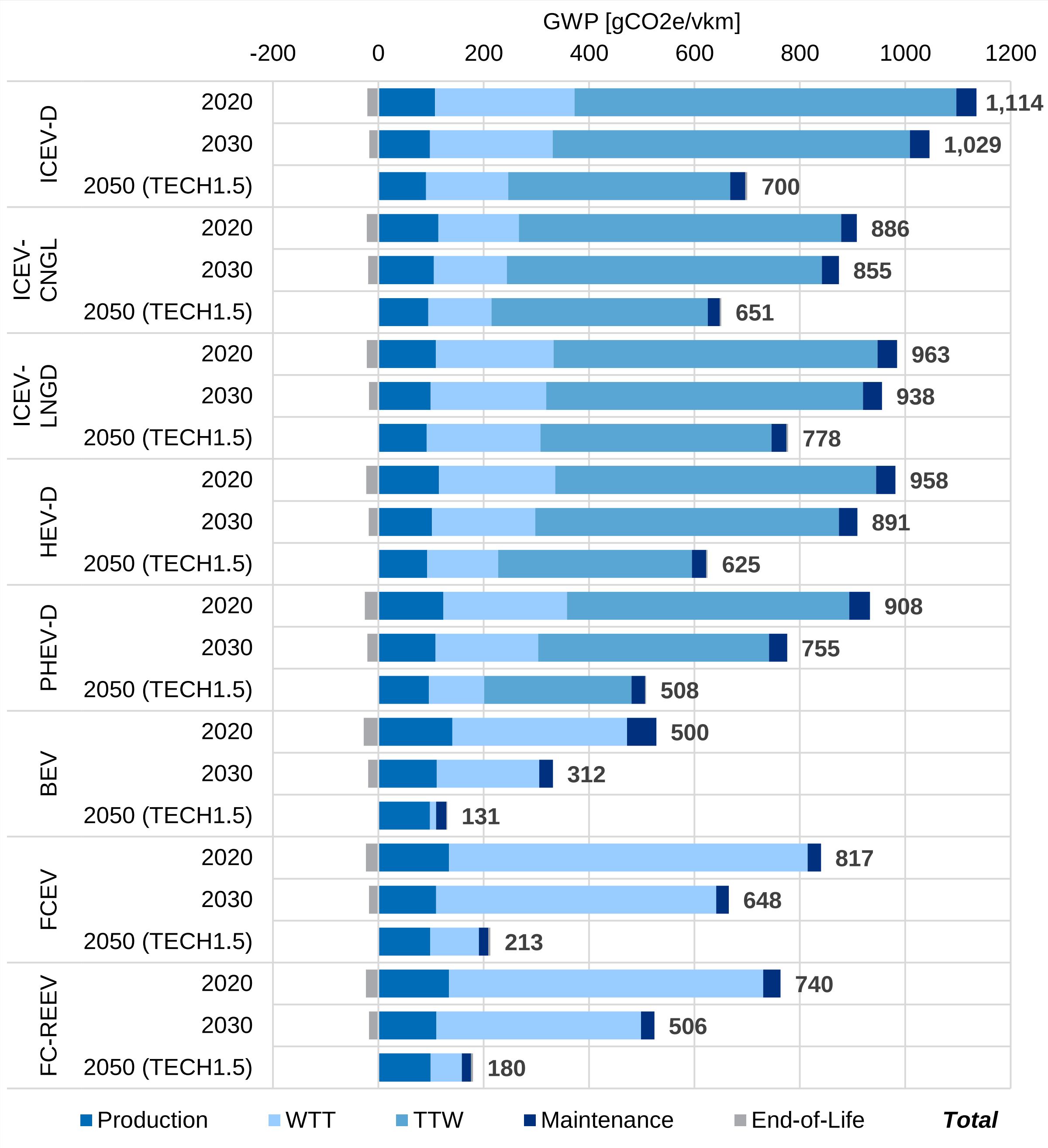
Notes: **Powertrain types**: G- = Gasoline, D = Diesel; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle.

Figure A91: Summary of breakdown of overall lifecycle GWP impacts for N1 Class III vans for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



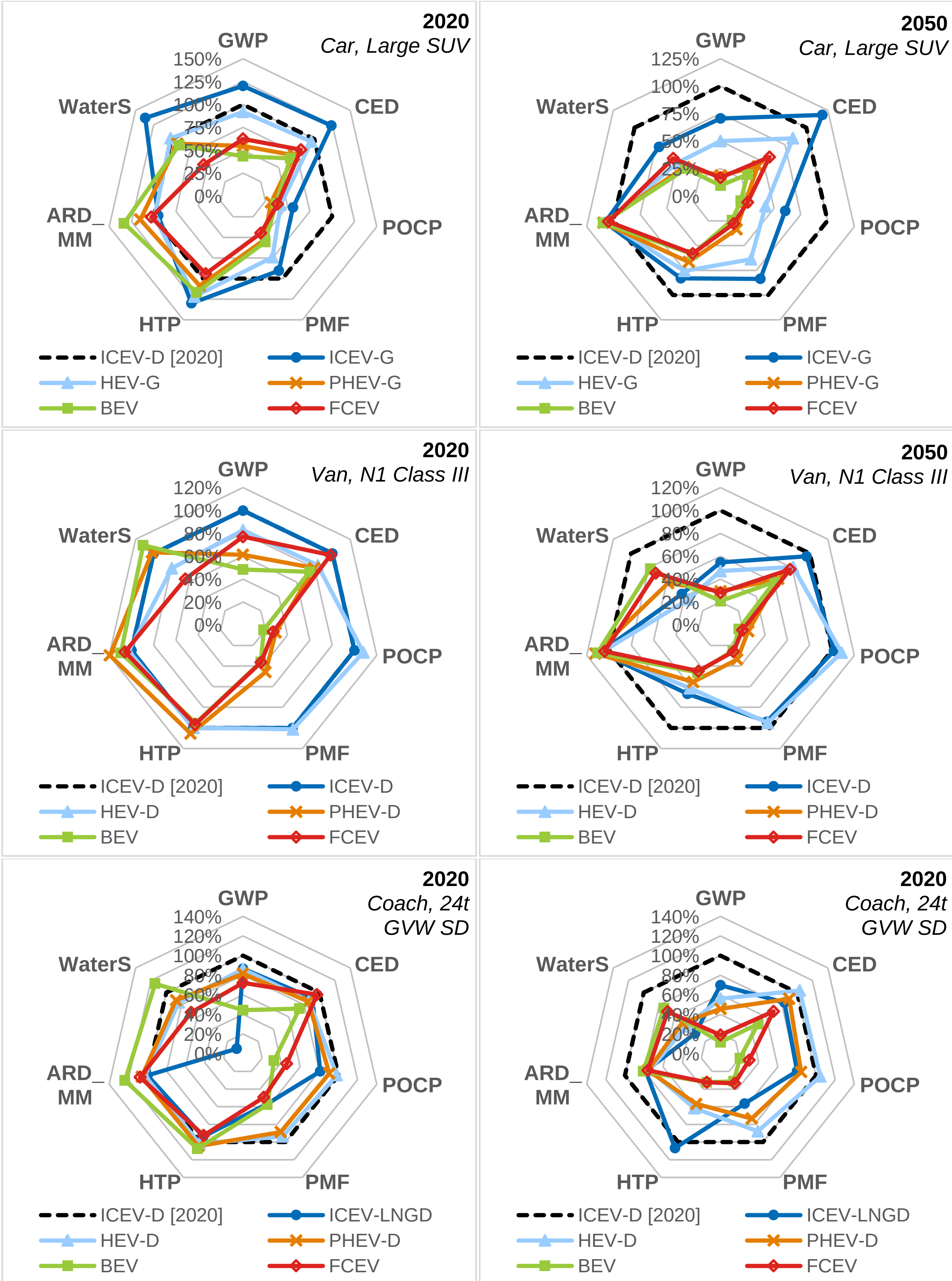
Notes: **Powertrain types**: G- = Gasoline, D = Diesel; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle.

Figure A92: Summary of breakdown of overall lifecycle GWP impacts for Coaches (24t GVW, single deck) for different powertrain types (Baseline scenario for 2020 and 2050, Tech1.5 scenario for 2050)



Notes: **Powertrain types**: G- = Gasoline, D = Diesel; ICEV = conventional Internal Combustion Engine Vehicle; LNGD = LNG HPDI engine, using ~5% diesel; CNGL = lean-burn CNG engine; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle. FC-REEV = Fuel Cell Range Extended Electric Vehicle.

Figure A93: Summary of the relative impacts for large SUVs cars, N1 Class III vans, and coaches for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050. Tech1.5 Scenario.



Notes: Total emissions are presented relative to a 2020 conventional Diesel ICEV = 100%.
LCA impacts: GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity

A6 Appendix 6: Considerations regarding the LCA methodology referred to in the CO_2 Regulations

The LCA methodology developed and applied under this project was aimed to enhance the general understanding of policy makers of the complex general environmental impacts of vehicle manufacturing, use and end-of-life on a quantitative basis. This study was thus not intended to provide an assessment of the possibility to develop methodologies for reporting life-time CO_2 emissions as foreseen under the vehicle CO_2 emission Regulations (EU) 2019/631 (LDV) and (EU) 2019/1242 (HDV). The aims of the latter would be more aligned with those of a product LCA, where some methodological choices or data may be different.

In this Appendix we explain in which areas the methodology developed in this study would not be directly suitable in that context (although many commonalities are expected) and we present our thoughts with regards to what elements would need to be considered differently in such case. A high-level summary of the main differences between 'Policy LCA' studies and 'Product LCA' studies is presented in Table A53 below. Many of the differences revolve around foreground data assumptions, e.g. the use of vehicle model-specific datasets, and the standardisation of certain input data/assumptions.

Table A53: Comparison between LCA for policy analysis and LCA for product environmental reporting

LCA Type	Audience and objective	Key differences between policy and product LCA
Policy Analysis	• **Primary intended audience** are policy-makers and academics • **Purpose** is to aid understanding of potential wider societal implications for policy development • **Impact** of product/service **within wider social system** • Subject may be **real or hypothetical/generic**	• **Wider** scope/boundaries with a more exploratory approach on method (e.g. on fuel chains) or datasets to enhance understanding on influence • **Generic** vehicle/powertrain types designed to be broadly equivalent/similar to aid comparison • Significant consideration of both **temporal** and **spatial** effects, e.g. linked to EC modelling scenarios • Wide variety of **impacts**, **sensitivities** to explore variation in key assumptions and uncertainties
Product Environ-mental Reporting	• **Intended audience** is customers and general public • **Purpose** is the quantification of impacts of manufacturer's **specific products** • **Certified** to conform to LCA standards, e.g. ISO, PEF • Results usually in Environmental Product Declarations (EPDs) or Corporate Responsibility Reports	• General LCA methods *may* be similar to policy LCA (likely with a tighter focus/boundary); usually align with regulation for fuels and electricity impacts ○ E.g. standard WTW **regulatory** defaults/average • Datasets for vehicles based on **manufacturer** / supply-chain data for **specific models**, and using also information from **type approval** • **GWP** (i.e. GHG) impacts at least, possibly others (e.g. cumulative energy, regulated pollutants) • Likely limited inclusion of temporal effects

In the following sections a high-level description of the differences between the application in this study, and a possible regulatory LCA (in the context of the provisions in the CO_2 regulations) is provided. A qualitative comparability rating is also provided for different elements, as follows:

R	Comparability rating (in the context of the provisions in the CO_2 regulations)
H	High comparability - few changes likely needed to the methods/approaches between this study and a possible regulatory LCA
H/M	Intermediate, some individual elements may be closer than others
M	Medium comparability – many elements are likely to be similar, but moderate changes may be needed need to methodologies or the basis of key datasets
M/L	Intermediate, some individual elements may be closer than others
L	Low comparability – likely to be significant differences between the two applications, more challenging elements to consider and/or major changes needed to methodologies and datasets

A6.1 Goal and scope

The Regulations setting CO_2 emission performance standards for cars/vans (Regulation (EU) 2019/631, Article 7(10)) and for heavy-duty vehicles (Regulation (EU) 2019/1242, Article 15(5)) both mandate the Commission to evaluate, not later than 2023, the possibility of developing a common Union methodology for the assessment, and the consistent data reporting of the full life-cycle CO_2 emissions of new vehicles that are placed on the Union market.

In that context, the goal of the LCA methodology would be a specific (absolute) and comparative quantification of CO_2 emissions on a product level. The object of investigation would thus be, for example, an actual passenger car (model) which should also be comparable to others. Harmonised data in a legislative context has only been used for tailpipe emissions (i.e. as indicated above) and energy consumption of vehicles (i.e. from type-approval certification), as well as for (bio-) fuels and electricity generation (e.g. default values for different fuels in RED II, FQD). For a regulatory methodology to report and assess full life-cycle CO_2 emissions, a range of additional standardised data would also need to be developed/set.

A6.2 Life-cycle inventory (LCI) data

Area	This Study (Policy LCA)	Regulatory LCA for assessing and reporting CO_2 emissions (Product LCA)	R
Background LCI	• Background LCI dataset based on specific materials /processes from Ecoinvent • Timeseries projection of future material impacts factored also into end-of-life calculation of recycling credits	• Definition/provision of a default set of LCI factors for key materials/processes to improve consistency/comparability • Providing a timeseries of default background LCI impacts for materials and processes is likely not feasible and would create significant burden/complexity for a possible regulatory approach/application, so is likely not appropriate.	M

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

For this study we used a general background LCI dataset based on specific materials and processes from Ecoinvent mainly (and in some cases GREET, where data was missing) – see Appendix A4.1. These data were further adjusted to develop a timeseries of impacts for key materials, so that certain future improvements (mainly from electricity decarbonisation) might be estimated both for manufacturing, and also in the end-of-life accounting (i.e. to determine recycling credits) under different scenarios.

For a possible regulatory application, it may be desirable to provide/define a set of default LCI values for key materials and processes to improve comparability between OEM LCA results. However, the development of a timeseries of impact factors would add further complexity and additional burden in the context of a possible regulatory LCA methodology/requirement. Further work would also be needed to address data gaps/areas of uncertainty or lower robustness in available LCI data for certain materials (e.g. carbon-fibre – primary and recycling/recycled material).

A6.3 Vehicle model specification datasets

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Fuel consumption /CO_2 emissions	• Defined based on generic average vehicles: regulatory test-cycle values adjusted to real-world performance based on LCA model settings	• Vehicle model specific datasets, most likely type-approval certified values. ○ Standardised regulatory to real-world uplift of these might be considered also (e.g. as per the US fuel economy labels).	M
Electric energy consumption	• As above.	• As above.	M
Electric range	• Input assumptions for type-approval cycle, adjusted to real-world range based on LCA model settings	• As above.	M
Unladen mass	• Generic averages for reference powertrains, values for other powertrains calculated relative to these	• Vehicle model specific datasets	M
Total battery energy capacity	• Calculated based on various input assumptions in the LCA model	• As above.	M

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

For a standardised reporting methodology, specific datasets relating to the actual vehicle model should be used. For example, this would include any general vehicle specifications, unladen mass and battery energy capacity, as well as any values for fuel/energy consumption and emissions per km defined by the regulatory processes.

A6.4 Other standardised datasets

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Activity and lifetime	• Assumptions on vehicle life and activity by vehicle type • Age-dependant profile of vehicle activity (used in combination with time profile for energy impacts)	• Standardised assumptions to be used for a specific vehicle category • Age-dependant profile may be too complex, but might be factored into default impact factors for fuel/electricity – see Sections A6.6/A6.7.	H /M*
Share of operation on different fuels / electricity	• Based on regulatory WLTP Utility Factor for LDVs • Estimated based on operational range and average daily mileage for HDVs	• Standardised based on regulatory definition (i.e. WLTP UF, * new methodology to be defined for HDVs, and for dual-/bi-fuel vehicles)	H /M*

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Test-cycle to real-world uplifts	• Standardised test-cycle to real-world uplift factors, and various other adjustments to real-world performance based on LCA model settings	• To be considered whether standard uplift factors might be included, e.g. similar to the approach used in the US fuel economy labels.	M
Load/occupancy factors	• Default assumptions and sensitivities on load factors to allow derivation of impacts per tonne-km for freight vehicles	• Standardised default/average values, possibly with max/min loading (e.g. as defined in certification for HDVs using VECTO-based certification) • Also included for passenger vehicles	H
Impacts from fuels or electricity	• Calculated based on specific settings for different regions, conditions, scenarios, time periods, fuel blend assumptions.	• Regulatory default factors set for fuels and electricity, see Sections A6.6/A6.7	M/L

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

For a regulatory LCA methodology, a number of other elements affecting CO_2 emissions would need to be standardised in the assessment to ensure greater comparability of the results, in a similar way to they have been handled in this study, including: assumptions on vehicle lifetime and mileage/activity (including default load factors, where relevant), any adjustment factors to convert fuel consumption / emissions from regulatory testing to real-world equivalents (if relevant), the methodology for estimating share of energy consumption for dual-fuel or PHEV/REEV powertrains. Clear definitions would need to be provided on the assumptions to use/how to account for the shares of operation on different types of fuels or electricity in the LCA for these.

For the impacts from consumption of fuel, hydrogen or electricity, standardised factors for emissions intensity would need to be defined – and potentially also how this changes over the vehicle lifetime. This is also discussed in Sections A6.6 and A6.7 below.

A6.5 Vehicle manufacturing, maintenance and end-of-life

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Manufacturing	• Generic datasets for manufacturing/process energy consumption, emissions and waste • Generic vehicle material composition for glider and components • Generic assumptions on recycled content / sourcing of materials • Generic ‘market average’ traction battery modelled	• OEM/supplier-specific datasets • Vehicle model-specific material composition • Potential definition of regulatory default datasets for impacts from production of specific materials • Possibility for bespoke assumptions for sourcing of key materials and recycled content? • Potential requirement of specific LCA of the traction battery, possibly other major components (e.g. fuel cells)	M/L
Maintenance	• Generic foreground data assumptions by vehicle and powertrain type for certain components and consumables	• Vehicle model-specific foreground datasets, e.g. based on recommended maintenance requirements set out in owner handbook	M

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
		• Potential regulatory defaults set for key materials/consumables or at least the definition of which should be included as a minimum with model-specific characterisation	
End-of-Life	• Impacts calculated using PEF Circular Footprint methodology, using recommended default parameters and assumptions on recycled content, recycling and recovery rates. • High-level methodology implemented for credits for repurposing/second-life application for batteries	• Many vehicle product LCA tend to use cut-off method (i.e. no net recycling credits), but PEF CR might be applied with the provision of default parameter assumptions. • Where manufacturer is putting in place specific provisions for battery recycling these could be used to supersede relevant default values where relevant/suitable evidence is available. • Further work is needed on data / methodologies and evidence for battery repurposing and second life.	M

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

The methodologies and data developed for this study are intended/designed to provide an objective harmonised comparison between different vehicle powertrain and fuel combinations, so use largely generic datasets/assumptions. The main shift for a possible regulatory LCA would be to move to OEM/supplier and vehicle model specific input datasets characterising their vehicles, manufacturing and supply-chains for vehicle manufacturing and for anticipated maintenance/servicing. A key consideration here would be on the minimum level of complexity that should be anticipated / required in this characterisation – i.e. balancing trade-offs between accuracy, comparability and analysis burden.

In addition, to facilitate more meaningful comparisons, it may be necessary to define standardised datasets to be used for the impacts from the production of major materials used in vehicles (i.e. impact factors for production of primary and secondary materials, processing materials into parts, recycling, recovery and disposal processes, etc).

For key components, such as batteries, possible options would include requiring a more detailed LCA for these components, or an approach similar to that used for bio/synthetic fuels: providing (conservative) default values (e.g. per kWh battery) with the option for manufacturers to use specific values based on their/their component supplier's own LCA.

The end of life approach also needs to be harmonised to make the results comparable, and should (most importantly) be adjusted to the policy goals. If the policy focus is on promoting recycling an avoided burden approach could be prescribed, if use of secondary materials and avoidance of primary materials is a key goal a cut-off approach could be preferred. The PEF CFF (Circular Footprint Formula) applied in this study's LCA seeks to strike a balance in this area in allocating benefits between recyclers and recycled material providers depending on the material. Consistency with this approach for the purposes of a regulatory LCA would seem appropriate, but would entail greater complexity (and therefore burden) than simpler approaches, even with the provision of suitable default values for relevant PEF parameters. Allowing manufacturers to use their own data for at least recycling rates, could also be an option to encourage improvements where they have implemented more direct control on their end-of-life responsibilities (e.g. development of specific collection and recycling and/or repurposing schemes for EV batteries).

For repurposing and second-use of batteries (or indeed any other components), more work is still needed to better understand the potential in this area and develop/agree suitable methodologies to apply to account for the potential impacts/credits for such activities from an LCA perspective.

A6.6 Fuel production

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Fuel chains	• Modelling of individual fuel chains (using alternative methodological choices)	• Defining default values (e.g. based on existing RED fuel defaults for GHG), • Further development of methodologies and data for individual fuel chains	M/L
Fuel blends	• Definition of alternative fuel blends based on scenarios for future deployment • Accounting for vehicle age-dependant mileage profile in the calculation of fuel impacts	• Potential definition of a standardised /average 'blend' used over the vehicle lifecycle ○ Possible simple accounting for age-dependant mileage considerations in the definition of defaults	M

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

For a regulatory LCA methodology in the context of the CO_2 regulations, it would likely be more appropriate to define set default impact factors for manufacturers to use in their LCA, based upon the existing regulatory defaults (e.g. as defined in RED II) to ensure a harmonised approach.

Other important considerations would include:

- Whether to develop average 'fuel blend'/'fuel mix' default factors to account for anticipated future deployment over the lifetime of vehicle use (i.e. analogous to changes in electricity mix).
  - Whether such defaults might also account for age-dependent mileage profiles.
- Consistency with the methodologies/boundaries and values for corresponding electricity default factors (see Section A6.7).

A6.7 Electricity production

Area	This Study (Policy LCA)	Possible Regulatory LCA (Product LCA)	R
Electricity chains	• Modelling of individual electricity chains	• Definition of a standardised EU average impact factors for specific generation types	H
Electricity mix	• Definition of grid generation mix based on scenarios for future change, for EU and individual countries • Accounting for vehicle age-dependant mileage profile in the calculation of impacts	• Potential definition of standardised /average grid mixes/impact factors used over the vehicle lifecycle • Possible simple accounting for age-dependant mileage considerations in the definition of defaults	H/M

Notes: R = comparability rating: H = high comparability (few changes needed), M = medium: similar, but moderate changes needed, L = low, significant differences, or more challenging elements or major changes needed.

The considerations for electricity production in a possible regulatory LCA application are similar to those for fuels, but without any pre-existing default values for impacts being defined in legislation. Similarly to fuels, it will likely be necessary to define a set default impact factors for manufacturers to use in their LCA for at least electricity use in the operational phase, although some consideration should also be given to the accounting for electricity consumption in vehicle/component manufacturing.

As for fuels, an 'average' electricity mix/impact factor could be defined to account for anticipated future developments over the life of the vehicle and potentially also accounting for age-dependant vehicle mileage considerations. Again, it would be important to ensure consistency in the methodology and boundaries, used to define the impact factors for fuels and electricity used by vehicles. For example, the current regulatory defaults for fuels do not include capital goods (i.e. for fuel production infrastructure), unlike the results developed for this study. However, since these are separated out in the accounting for electricity in our study, the option would be available to use our results with these excluded.

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