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Industrial Innovation: Pathways to deep decarbonisation of Industry.

Part 1: Technology Analysis

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A report submitted by [ICF Consulting Services Limited](#) and [Fraunhofer ISI](#)
to the European Commission, DG Climate Action

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Introduction

The Paris Agreement¹ on climate change has the objective to keep global temperature increase to below 2°C and to pursue efforts to limit the increase to 1.5 °C above pre-industrial levels. To achieve these targets, energy intensive sectors will need to contribute significant emission reductions. The extent to which key EU industrial sectors can benefit and contribute to a climate-neutral future will depend on their ability to implement existing technologies, and the continued development and commercialisation of new products and breakthrough technologies.

This report was undertaken by ICF in association with Fraunhofer ISI and DIW Berlin. Its purpose is to detail the promising low carbon technologies and product developments available and that can lead to deep decarbonisation of the energy intensive industry sectors by 2050 and beyond.

¹ <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

Part 1: Technology Analysis

The aim of this report is to assess the decarbonisation options that could be employed in the European chemicals, refineries, iron and steel, non-ferrous metals, non-metallic mineral and pulp and paper. Table 1.1 presents the sectors and subsectors included within the scope of the analysis. In 2015, these sectors accounted for over 80% of total industrial energy consumption, and 91% of non-fuel combustion related greenhouse gas (GHG) within EU ETS sectors.

Table 1.1 Pertinent subsectors included within the scope of this report

Sector	Pertinent subsectors
Chemicals	Ethylene, Ammonia
Petroleum refineries	Petroleum products
Iron and steel	Primary and secondary steel production
Non-ferrous metals	Primary and secondary aluminium and copper production
Pulp and paper	Pulp (mechanical and chemical production), paper (all grades)
Non-Metallic Mineral	Glass, Cement, Lime, Ceramics

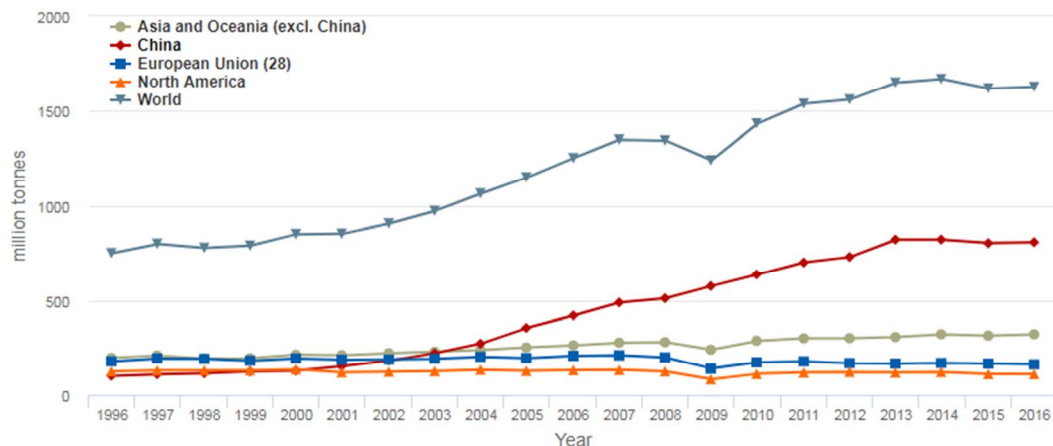
As the report looks at a time horizon of 2050 (and beyond), the business environment for these industrial sectors will evolve significantly over time due to economic, environmental, social, political and technological changes. As such, this report, first presents the core products associated with each sector/product. Subsequently, the report details the various processes/methods/fuel options for decarbonisation. The current processes and Best Available Technologies (BAT) are described for the reference scenario. Innovative solutions have been researched and are presented with their carbon saving potential and Technology Readiness Levels (TRL).

1 Iron and Steel

1.1 Core Products

Figure 1.1 provides a comparison of global steel production across key nations. Global production has been growing steadily since 1996, and even more rapidly from 2004 onwards. However, overall growth was mainly attributed to Chinese production, while other nations have remained relatively flat.

Figure 1.1 Global comparison of crude steel production from 1996 - 2016²



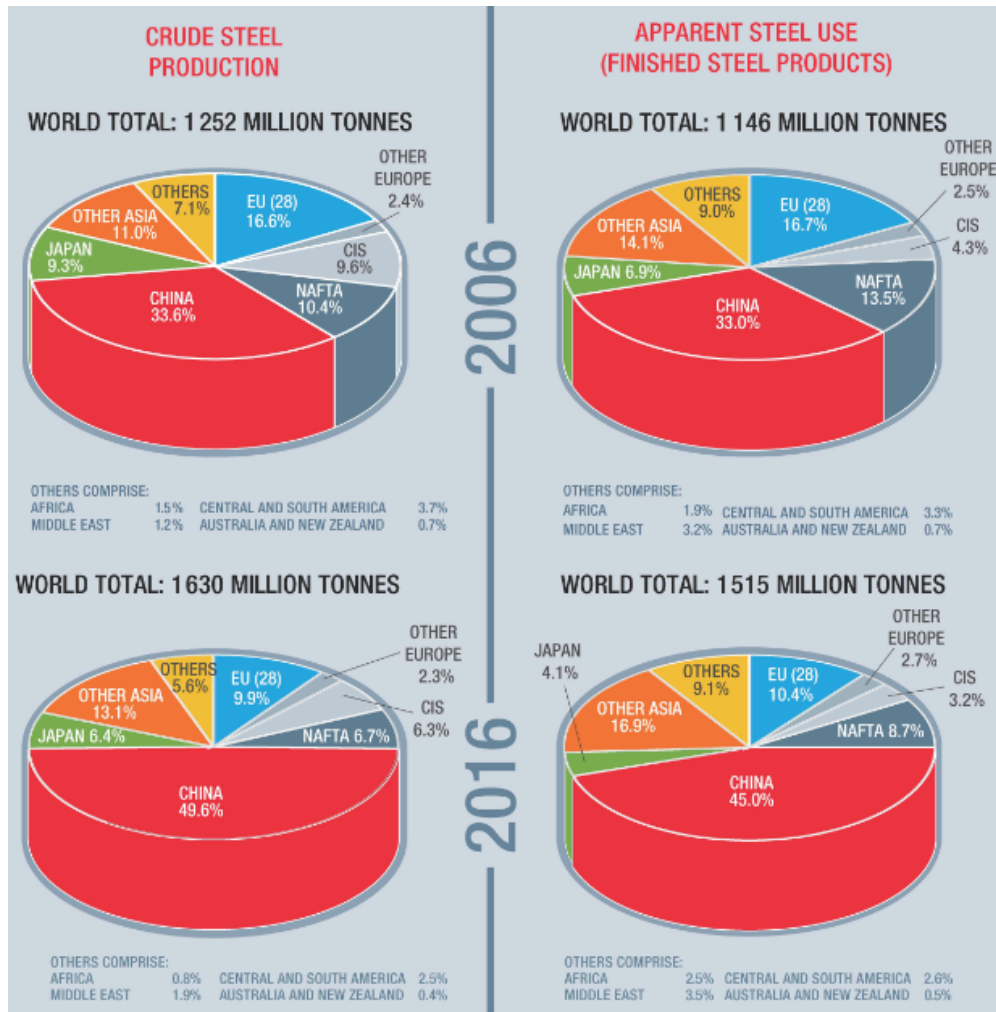
China remains the largest producer, currently accounting for > 800 Mt/y. It is followed by Japan, India (growing rapidly), USA (declining), Russia and South Korea.

In 2016, the EU-27, as a combined entity, was the world's second largest steel producer after China, accounting for nearly 10% of the world's total steel output. However, drilling down, Germany is the largest EU steel maker, but is ranked 7th in the World, with Italy second in EU but 11th in World. Other notable steel producers include France, Spain, Poland, UK and the Benelux countries. The EU-28 reduced its steel production by 22.9% from 210.3 Mt in 2007 to 162. Mt in 2016. (World Steel 2017).

Figure 1.2 provides a summary of the top steel production and steel finished products consuming countries in 2006 and 2016.

² World Steel Association (2017)

Figure 1.2 Top crude steel production and finished product steel use countries³



1.1.2 Products

Iron and steel products are grouped into three main categories: Crude steel, semi-finished products, and finished products.

1.1.2.1 Crude steel

Crude steel is used to make semi-finished and finished products destined for the consumer market or as inputs for further processing.

In the EU, approximately 40% of the total crude steel is produced by electric arc furnace (EAF) technologies, with the remainder (60%) produced by blast furnaces-basic oxygen furnaces (BF-BOF). This apportionment has been relatively constant for the past 10 years (2007 – 2016).

1.1.2.2 Semi-finished products

Semi-finished products include steel shapes (blooms, billets or slabs) that are later rolled into finished products such as beams, bars or sheet. Continuous casting is the

³ World Steel in Figures 2017, World Steel Association, 2017

process whereby molten metal is solidified into a semi-finished billet, bloom, slab or beam blank.

1.1.2.3 Finished products

Finished products are subdivided into three main types, flat and long products, and alloyed steels.

- Flat products include slabs, hot-rolled coil, cold-rolled coil, coated steel products, tinplate and heavy plate. They are used in automotive, heavy machinery, pipes and tubes, construction, packaging and appliances⁴. Flat products represent approximately 60% of the EU hot rolled steel output.⁵
- Long products include billets, blooms, rebars, wire rod, sections, rails, sheet piles and drawn wire. The main markets for these products are construction, mechanical engineering, energy and automotive.
- Alloyed steels, which are sometimes also called special steels and may be considered specialty products, account for a relatively small portion of all finished steel products. The most important of these is stainless steel.⁶

1.1.3 Value chain

- Steel is a major component in buildings, tools, appliances, automobiles and various other products. The steel industry primarily supplies the construction sector, the automotive sector, the packaging industry, the consumer goods industry (domestic appliances etc.), and the electrical and mechanical engineering sector (see Figure 1.3).
- Automotive and construction sectors have usually been the two largest steel end users (accounting for over 50% of total EU consumption in 2010). Therefore, fluctuations in turnover in these industries significantly affect steel demand.⁷
- Other important consumers are steel pipe and tube producers, manufacturers of metal products such as radiators, tools, locks and fittings, and ship builders, which together account for over 30% of the market.⁸

⁴ ArcelorMittal product information

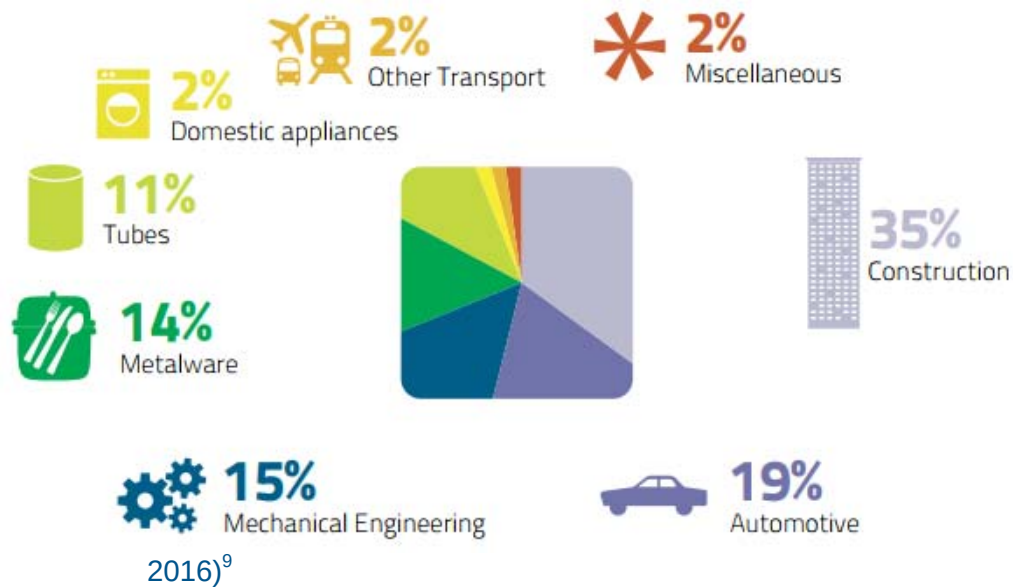
⁵ Ecorys, 2008

⁶ Study on energy efficiency and energy saving potential. ICF 2015

⁷ Study on energy efficiency and energy saving potential. ICF 2015

⁸ Deutsche Bank Research, 2009

Figure 1.3 EU sector shares in total steel consumption (average from 2012 –



1.2 Decarbonisation technologies

There are three primary pathways to achieve decarbonisation of the steel industry.

The first pathway focuses on recycling scrap steel. It is expected that by 2050, scrap availability will have increased to such an extent that a large share of today's steel production could be provided through the recycling of scrap – but only if secondary steelmaking can 1) reach steel qualities that currently can only be provided by primary steelmaking and 2) sufficient electricity from renewables is available. Besides that, steel can have different percentages of elements such as nickel, chromium, molybdenum, chrome or carbon, which give them different properties. The extra effort required to sort and distinguish scrap metal, renders the prospect of recycling scrap steel unappealing without further improvement in collection and sorting technologies.

Second, the CO₂-intensive off-gases from the steel industry could be either used as input to the chemical industry (carbon capture and usage, CCU) or they could be stored underground (carbon capture and storage, CCS). CCU requires additional energy and the huge amounts of off-gases from the steel industry could result in decreases of product prices. CCS is also a potential decarbonisation option, but steelmaking processes are, so far, not ready to apply CCS.

The third pathway aims to produce steel using renewable energy. Currently discussed options include, the electrolysis of iron ore, the direct reduction of iron with hydrogen or plasma-smelting of iron ores. Out of these, direct reduction based on hydrogen seems to be the technology with the highest TRL. Nonetheless, the development of electrolysis has made progress in recent years and it might offer a more energy-efficient option than the hydrogen-based direct reduction.

⁹ European Steel in Figures, Eurofer, 2017

Table 1.1 and Table 1.2 present the summary of decarbonisation options for the iron and steel sector.

Table 1.1 Technology readiness levels of selected mitigation options in the iron/steel sub-sector

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency		Smelting reduction	Top-gas recycling	Near net shape casting	
Fuel switch		DRI RES Electrolysis	DRI RES-H2 Plasma		
CCS and CCU			CCS		
Recycling and re-use			CCU		
Material efficiency (downstream)			High quality EAF		
Material substitution (downstream)					

Table 1.2 Main characteristics of selected mitigation options iron/steel sub-sector¹⁰

Technology option	Examples	TRL	Max. emissions reductions ¹¹	Energy savings ¹²	Market entry	Reference Technology
Hydrogen based direct reduction (H2-DR)	HYBRIT, GrINHy, H2Future, SuSteel, SALCOS	7	up to 95%	20%	2030/2035	BF/BOF steelmaking
Electrolysis of iron ore	SIDERWIN, ULCOWIN	6	up to 95%	40%	2040	BF/BOF steelmaking
Smelting reduction (without CCS)¹³	Hlsarna	5 ¹⁴ -6	up to 35%	20%	2025[e]	BF/BOF steelmaking
Top gas recycling blast furnace (without CCS)¹⁵	ULCOS-BF, IGAR	7	up to 25%	15%	2025+	Blast furnace

¹⁰ Fishedick et al. (2014), Van der Stel (2013), Van der Stel (2017), Pardo und Moya (2013), WSP Parsons Brinckerhoff und DNV-GL (2015), Fleiter et al. (2013), own estimations [e]

¹¹ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

¹² Energy savings show the reduction in energy consumption resulting from the technology change

¹³ Higher potentials with CCU/S: up to 80%.

¹⁴ Pilot plant in the Netherlands IJmuiden.

¹⁵ Higher potentials with CCU/S. up to 60%.

Technology option	Examples	TRL	Max. emissions reductions ¹¹	Energy savings ¹²	Market entry	Reference Technology
Carbon capture and usage	Carbon2Chem, Steelanol	5-7	tbd	tbd	2030+	BF/BOF steelmaking & production of chemicals
Near net shape casting	Castrip, Salzgitter, ARVEDI ESP	8-9	up to 60%	60%	2020+	Conventional hot rolling processes

1.2.1 Conventional production methods

Globally steel is produced using three main processes:

- Primary steel making in blast furnaces (BF) and basic oxygen furnaces (BOF), i.e. converting the iron-ore using coal and other substances into hot metal then further processing this into value-added product such as finished steel sheets, shapes, bars or wire. This is globally the dominant production route, especially due to China's large share.
- Primary steel making using direct reduction plants. Iron ore may also be reduced below its melting temperature in direct reduction plants that are run either with natural gas or with coal. The direct reduced iron (DRI) is then fed to an electric arc furnace to make steel. This is a commercial technology, but it is not largely used.
- Secondary steel making. Steel scrap can be re-melted in electric arc furnaces (EAF). Since the raw material iron must have been reduced in primary steelmaking, this production route requires less energy. Its main energy carrier is electricity. Thus, if the electricity is provided by renewable energy, this steel production route has very low CO₂-emissions.

Figure 1.4 provides an overview of the key processes in EU iron and steel production.

Primary iron and steel making involves the following key stage processes; raw material preparation, iron making and steel making process.¹⁶

- **Raw material preparation.** During this stage, coal is converted into coke through a pyrolysis process in a coke oven plant, producing coke (solids which are raw material fed into the iron making process), coke oven gas (used as fuel after cleaning) and liquids. The operating temperature of the coke oven gas is between 1150 – 1350 °C. To improve the iron ore reduction process in the next stage, the raw materials go through sintering (a process of mixing raw materials with additives before charging into blast furnace) or palletisation (a process of forming raw material mixture into 9 – 16mm spheres through high temperature process). During the 2005 – 2008 period, there were 34 sintering plants and 6 pellet plants within the EU¹⁷.
- **Iron making process.** The raw material (coke, sinter / pellets, lump ore) is fed into the Blast Furnace (BF) that reduces the iron oxides to metal iron. The liquid

¹⁶ Study on energy efficiency and energy saving potential. ICF 2015

¹⁷ JRC BREF, 2012

iron (hot metal or 'pig iron') is collected and continuously cast. This process also produces BF gas which is collected and treated before being utilized as fuel.

- **Steel making process.** The key objective of this stage is to regulate the impurities within the hot metal feedstock. As a result, carbon content is reduced to a specified level (from 4 – 5% to 0.01 – 0.4%), contents of desirable foreign elements are regulated, and undesirable impurities are burned (oxidised) in the Basic Oxygen Furnace (BOF). The liquid molten steel from the BOF is then cast into crude steel forms (slabs, blooms, billets) for further processing.¹⁸

Secondary steel making process involves direct smelting of materials containing iron typically from scrap and recycled iron feedstock from waste streams, essentially omitting the energy intensive process of coal pyrolysis and iron ore reduction. In this process, the scrap iron is melted and refined utilising high amounts of electric current, carried out in an Electric Arc Furnace (EAF).

Finishing. There are two main classifications of finished steel products; flat and long. Long products go through further finishing to form seamless pipes, bars, rolls or wires. Flat products go through a finishing process to form cold rolled sheets, steel plates, welded pipes, coated sheets, etc.

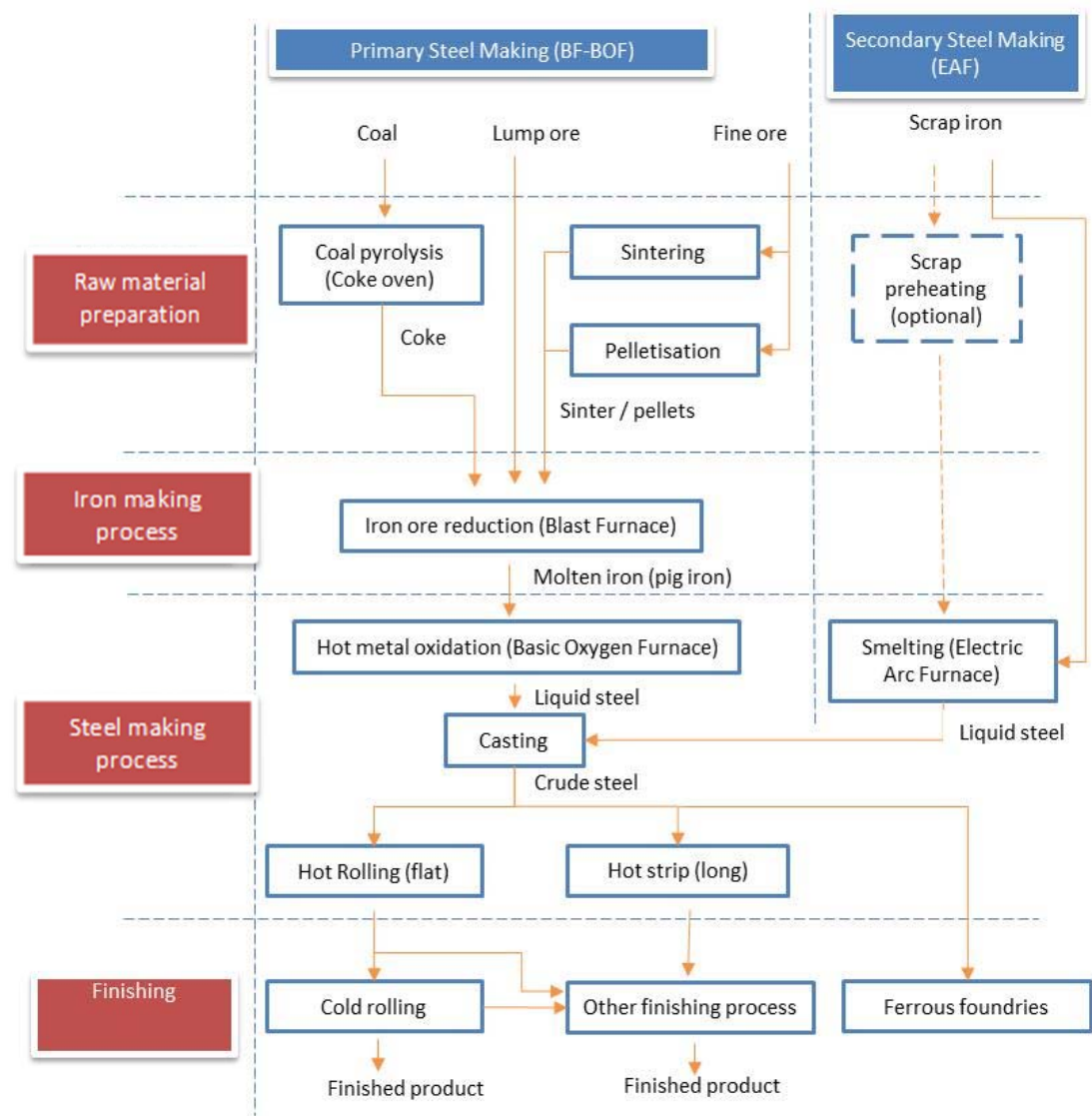
In 2006, there were 86 BF installations, 101 BOF installations and 231 EAF installations within EU¹⁹. The BOF and EAF process has since replaced the less efficient Open-Hearth steel making process. Within the EU, the BF-BOF and EAF are the only processes being used for steel making. There is also one direct reduction plant which represents 0.2% of total EU production.²⁰

¹⁸ Study on energy efficiency and energy saving potential. ICF 2015

¹⁹ JRC BREF, 2012

²⁰ Study on energy efficiency and energy saving potential. ICF 2015

Figure 1.4 Conventional primary and secondary metal production routes²¹



The shift from primary steelmaking to the scrap based secondary steelmaking depends on the availability of scrap metal within the EU market and on the qualities of the required steel grades. The fundamental shift from primary to secondary steelmaking is thus business-as-usual. Secondary steelmaking already has the potential to almost completely decarbonise if the electrical energy is obtained from renewable energy sources. In 2016, 39.5 % of crude steel production in the EU 28, or 64.0 Mt, was produced based on scrap (World Steel 2017). BCG (2013) expects that scrap availability in the EU-28 will increase to 136 Mt in 2050.

²¹ Study on energy efficiency and energy saving potential. ICF 2015

1.2.2 Incremental CO₂-reductions with BATs

1.2.2.1 Optimisation of coke batteries and sinter plants

Coke Dry Quenching (CDQ). The coke oven produces hot coke. Water cools the hot coke quickly for quality purposes, whereby the heat content of cooling water is lost to the atmosphere. CDQ cools the coke by circulating a non-active gas (such as nitrogen) in the cooling chamber. The heat recovered by this gas is used to generate high-pressure steam and then electricity by a turbine. A further advantage of CDQ is that it uses less water, which is an issue in dry or cold regions.

Sinter plant waste heat recovery. Sinter feed is deposited as a bedding, whereby coke in the upper layer is ignited. As the sinter bed moves forward, air is drawn through the bed to maintain combustion of the coke. Two systems can be used to recover energy from the sintering process:

- exhaust gas from the sinter bed can be returned to the sinter bed as combustion air;
- energy from the hot sintered ore is recovered at the end of the sinter bed, using a sintered ore cooling system. The hot air is applied for steam generation.

1.2.2.2 Optimisation of Blast Furnace (BF)

Optimised sinter pellet ratio. Blast furnaces in Europe typically have a low pellet ratio. Pellets, that have a higher iron content than sinter, reduce the CO₂-emissions of blast furnaces, but emit CO₂ in pellet plants. On the global level there is virtually no CO₂-reduction through the consumption of pellets in blast furnaces.

Pulverised Coke Injection (PCI). The primary function of PCI is to lower coke consumption during the iron ore reduction in blast furnaces. Thus, energy and CO₂ savings are realized through a decrease in coke production in coke ovens. Additionally, the savings are partly offset through an increased coal demand by PCI. In 2015, 62.2% of operating blast furnaces in EU-28 were equipped with PCI (Plantfacts 2015).

Top Gas Recovery Turbine (TRT). A TRT utilises the pressure difference from the top gas of high-pressure blast furnaces to ambient pressure to generate electricity. By 2015, 19 high-pressure blast furnaces in operation in the EU-28 were equipped with TRT while 22 were not (Plantfacts 2015).

Stove waste gas heat recovery. Hot blast stoves contain a fossil fuel burner to preheat the air intake fed into the blast furnace. A heat recovery system improves the efficiency of the hot blast stove, as thermal energy from the waste gas discharged is partially recovered (with external heat exchangers or recuperative burners) to pre-heat the blast furnace gas and/or combustion air. There are currently 18 hot blast stoves with waste heat recovered in the EU.

1.2.2.3 Optimisation of Basic Oxygen Furnace (BOF)

BOF waste heat recovery. In BOF steelmaking, a charge of molten iron and scrap steel along with some other additives (manganese & fluxes) is heated and refined to produce crude steel. An oxygen lance is lowered into the convertor and pure oxygen is blown into the furnace. The carbon in the steel reacts with Carbon Monoxide (CO) to produce Carbon Dioxide (CO₂), which leaves the convertor. At present, waste heat from the BOF gas is partially recovered to heat up the cold steel scrap fed into

the BOF as 'pre-charge' feedstock. Two additional systems are available to recover remaining heat from the BOF gas:

- Combustion of BOF gas in the converter gas duct and recover heat through a waste-heat-recovery boiler.
- Processing and storage of BOF gas in a gasholder for further use.

There were 22 BOF WHR system installed in the EU in 2012.

1.2.2.4 Alternative iron ore reduction methods

COREX process²². This is an alternative process to blast furnaces in reducing iron ore. In this process, lump iron ore and/or pellets and additives are loaded into the top of a reduction shaft. Reducing gas from the melter-gasifier is injected into the lower part of the shaft to reduce the iron ore to sponge iron. The additives ensure an adequate slag basicity, and sulphur is removed from the hot metal in the melter-gasifier. Although it has some limitations, the process offers the following benefits:

- No need for coking,
- Fuel savings of ~18%
- Reduced oxygen consumption of ~13%
- Reduced GHG emission of ~20%
- Other reduced emissions: ~30% less NOx, no VOC; significantly lower SOx
- Reduced investment and operation costs
- Lower slag production (18% reported)

The COREX process is installed and operating in South Africa, India, China and Korea.

FINEX process²³. Broadly similar to COREX, main difference is that FINEX process is capable of using iron ore directly as sinter feed. Fine iron ore is charged in a series of fluidized-bed reactors. As it passes down the reduction shaft it is simultaneously heated and reduced to give a Direct Reduced Iron (DRI) by means of the upward flowing reduction gas. Benefits include:

- Allows use of fine concentrates therefore omitting the need for pellet, sinter, or agglomeration of iron-bearing materials
- Capital cost (claimed) to be 20% lower than Blast Furnace
- Reduced production cost of ~15%
- Reduced GHG emissions (due to lower energy and no coking required)
- Valuable export gas for other metallurgical processes or co-gen electricity.

It known to be commercially available, but to date very low take-up. It is installed at POSCO, Korea

1.2.2.5 Optimisation of Electric Arc Furnace (EAF)

Oxy-fuel burners. Oxy-fuel burners utilise pure oxygen as fuel, which increases the flame temperature due to the omission of nitrogen in the air, resulting in reduced fuel consumption. EAF applies high intensity electrical energy between electrodes to create an arc that melts steel scrap. Modern EAFs use oxygen-fuel burners to provide thermal energy to the cold-spots of the furnace, heating the steel in a uniform manner, thus reducing the electricity consumption through optimised heat

²² Iron ore reduction process developed by Siemens

²³ Iron ore reduction process, similar to COREX but with additional capabilities, also developed by Siemens

transfer. In 2012, 136 oxy-fuel burners were installed in the EU steelmaking plants. Oxyfuel is also prevalent in other industries with furnaces, however, additional energy required for separation of O₂ from air should be taken into consideration.

EAF scrap pre-heating. Approximately 20% of the energy input to the EAF for melting the scrap metal is lost in the form of waste gas. Preheating scrap by using the waste gas heat of the furnace to preheat the incoming scrap metal charge will reduce the power consumption in the EAF process. In 2012, there were 99 Scrap Pre-heating systems installed in the EU.

CHP from waste heat. A waste-heat-recovery boiler can generate electricity offering a 7.5% reduction in EAF energy requirements. The process is commercial, but low uptake, largely because of harsh working environment in EAF; i.e., the presence of chemical substances such as acids and high temperatures.

1.2.2.6 Reheat furnaces (for non-integrated steel plants)²⁴

High Efficiency Burner. Advancements over the recent years include the commercialization of self-recuperative and self-regenerative burners that use staged combustion to achieve flameless combustion. This results in more uniform heating, lower peak flame temperatures, improved efficiency and lower NO_x emissions

Flue-gas monitoring. Stack thermometers, fuel meters, make-up feed water meters, oxygen analysers, run-time recorders, energy output meters, and return condensate thermometers are required to maintain a proper air-to-fuel ratio to optimize fuel combustion efficiency

Combustion optimization. Following above, combustion efficiency can be improved by continually monitoring (and adjusting) the air-to-fuel ratio to reduce excess air. Too much excess air carries away excessive amounts of heat in the excess oxygen (and nitrogen)

Exhaust gas heat recovery. Exhaust gas heat recovery increases efficiency because it extracts waste energy from the exhaust gases and recycles it back to the process, which reduces fuel/steam requirements.²⁵

²⁴ Study on energy efficiency and energy saving potential. ICF 2015

²⁵ Study on energy efficiency and energy saving potential. ICF 2015

1.2.3 Decarbonisation with CCS

1.2.3.1 Carbon capture and usage.

Carbon dioxide from industrial processes, such as from steelmaking, could be used as input to the chemical industry (carbon capture and usage, CCU). Carbon dioxide could be used to feed algae or for the synthesis of chemicals. Although this idea is appealing, there are some constraints. First, using CO₂ typically requires additional energy to produce further substances. Second, the amount of CO₂ released by the steel industry typically exceeds the quantity of the products that could be made of it (e.g. waxes, methanol). Third, products from CCU should keep the containing CO₂ over a large period, limiting the range of possible products.^{26,27,28}

Arcelor Mittal started to build a demonstration plant that converts blast furnace gas into bioethanol using a microbial gas conversion system at its site in Ghent, Belgium, in 2018 with a budget is 150 million Euro. First production is expected for mid-2020.

ThyssenKrupp runs the Carbon2Chem project that aims at producing chemical substances such as urea or methanol from CO₂ and other top-gases from the steel industry such as nitrogen and hydrogen. Those processes will require additional energy that will be supplied from renewable energy. Commercialization is scheduled beyond 2030. The project is funded by the German Ministry for Education and Research (BMBF)²⁹.

1.2.3.2 Carbon capture and storage (incl. the Ulcos projects).

Carbon capture and storage (CCS) has the potential to make deep emission cuts in several industries, such as the iron and steel sector while maintaining today's production routes. However, there has been limited progress on developing CCS for industrial processes, especially in the iron and steel sector. Globally there are two CCS projects that are directed to the steel industry. The European top-gas recycling blast furnace (see below) and a commercial CCS plant that has been erected at a direct reduction plant in the Middle East in 2016³⁰.

The Ulcos project was a European research project with 48 stakeholders and a budget of 35 million Euro that was run from 2004 to 2010 aiming at reducing CO₂ emissions by at least 50%³¹. Under this project, four technologies have been identified and have been developed to a certain extent. Three of them were based on carbon capture and storage (top-gas recycling blast furnace, HIsarna, Ulcored). The fourth technology is the electrolysis of iron ore (see above). While there is still some R&D on the top-gas recycling blast furnace and HIsarna (see below), little is published on the direct reduction plant.

²⁶ EUROFER (2017): Finance for Innovation: Towards the ETS Innovation Fund. Workshop 1: Ferrous and Non-ferrous metals. Presentation. Unter Mitarbeit von Dr.-Ing. Jean Theo Ghenda. The European Steel Association.

²⁷ thyssenkrupp (2018): Carbon2Chem

²⁸ ArcelorMittal (2017): Finance for Innovation: Towards the ETS Innovation Fund. Low C steelmaking in ArcelorMittal. Presentation. ArcelorMittal. Brussels.

²⁹ FONA (2018): Carbon2Chem. Bundesministerium für Bildung und Forschung.

³⁰ Global CCS Institute (2017): Projects database, Abu Dhabi CCS (Phase 1 being Emirates Steel Industries).

³¹ IETD (2018): Industrial Efficiency Technology Database. Ultra-Low CO₂ Steelmaking (ULCOS).

Smelting reduction (with CCS) combines coal preheating and partial pyrolysis incorporating a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. The process uses fossil fuels like e.g. coal as energy source but since energy-intensive coke- and sinter making are omitted, CO₂-emissions might be up to 20% lower than current coal-based primary steelmaking. The process is designed so that CCS can be applied.³²

Hisarnas current maximum annual production capacity is 60,000 tons of liquid iron, i.e. about the weekly production of current blast furnaces. A six-month-campaign was announced for 2017, but no results are reported (Tata Steel 2018).

Top gas recycling blast furnace (with CCS). Top gas recycling removes via a capture system the CO₂ from the top gas of the Blast Furnace and recovers useful components such as carbon and hydrogen. The reducing gas is then recycled back into the reactor allowing a reduction of the coke rates compared to a conventional blast furnace (BF). To facilitate the CO₂ removal, the system is operated on pure oxygen instead of air-based hot blast. A demonstration plant of the top-gas recycling blast furnace was planned, an additional funding was also permitted, but it has not been built until today. However, this concept seems to be further developed.

Near net shape casting. Near net shape casting encompasses various technologies that lead to a considerable shortening of the process-chain from liquid steel to the final steel product. Therefore, it can substitute conventional continuous casting plants, reheating furnaces and part of the roll stands. New efficient casting processes offer high saving potentials as they reduce the need for repeated reheating and consequently energy demand³³. However, there is no rapid uptake of this technology so far.

1.2.4 Decarbonisation with Novel techniques

1.2.4.1 Increased production of scrap-based steelmaking in applications for high quality steel

The CO₂-emissions from the steel industry could be strongly reduced if primary steel from blast furnaces were replaced with secondary steel. In secondary steelmaking, steel is produced from steel scrap and electricity. If the electricity is from renewable energy, the production of recycled steel could be close to CO₂-free.

Although the amount of available scrap is currently not sufficient to replace primary steel production; scrap availability in Europe is expected to increase continuously towards 2050. A study for Steelinstitute VDEh³⁴ assumes an increase of total scrap availability in the EU27 from 98 million tons in 2011 to around 136 million tonnes in 2050. Combined with innovative collection and sorting technologies (e.g. robotic cutting and handling or laser induced breakdown spectroscopy to allow automated sifting of mixed waste streams) a strong increase in the share of electric steel production appears possible including the use of EAFs as substitutes for higher-

³² EUROFER (2014): A Steel Roadmap for a Low Carbon Europe 2050. Hg. v. The European Steel Association, zuletzt geprüft am 13.06.2017

³³ Fleiter, Tobias; Schlomann, Barbara; Eichhammer, Wolfgang (2013): Fraunhofer-Gesellschaft Energieverbrauch und CO₂-Emissionen industrieller Prozesstechnologien - Einsparpotenziale, Hemmnisse und Instrumente. Stuttgart: Fraunhofer Verlag (ISI-Schriftenreihe Innovationspotenziale).

³⁴ BCG 2013

quality primary steel production. Other options supporting this assumption include the purification of molten scrap steel (e.g. sulphide matte, chloride slagging, preferential melting), new processes (e.g. belt casting), new product design reducing the use of unwanted elements or enabling easier separation³⁵. Thus, in the medium to long term, secondary steelmaking is likely to replace larger shares of primary steelmaking.

Mitigation potential

EAF steel production has an energy saving potential of roughly 70% and can result in an estimated direct CO₂-emission reduction of more than 90% compared to a conventional blast oxygen furnace when using renewable electricity.

Costs and TRL

Currently, Voestalpine is building a new steel plant in Austria that uses an electric arc furnace to melt down ultra-pure scrap combined with various alloy metals into special steels (e.g. for aircraft components, tools for the automotive industry, equipment for the oil and gas industry) in a digitalized production process using only electricity generated from renewables (Voestalpine 2018). Although this technology is already well developed, it is currently not widely used for high-quality steel production due to the above-mentioned limitations of using scrap as a raw material. The mentioned Voestalpine first-of-a-kind-plant needs an estimated investment volume of around 350 million Euro with an output of 205,000 tons high-quality steel per year³⁶.

1.2.4.2 Hydrogen-based steelmaking - direct reduction of iron ore (H₂-DRI) & plasma smelting reduction

The direct reduction of iron ore with hydrogen from renewable energy and the electric arc furnace offers a steel production process that could be close to carbon free, if the hydrogen is produced from renewable energy. Direct reduction of iron ore based on the consumption of natural gas is a commercially available process. In 2017, 87 million tons of direct reduced iron (DRI) have been produced globally, of which 82.4% was gas-based while 17.6% were coal-based. Key DRI producing countries are countries with large resources of natural gas (Iran, Russia, Mexico and Saudi Arabia) or India that uses the coal-based DRI-process.

To substitute coal based primary steelmaking with steelmaking based on the direct reduction of iron ore with hydrogen, the renewable hydrogen has to be available in the required quantities and at cost-competitive prices. A Proton Electron Membrane (PEM) electrolyser could produce renewable hydrogen (this is detailed further in section 2.2.2.5).

Hydrogen based steelmaking is currently an intensively researched technology. The potential TRLs might range from 5 to 7 depending on the specific concept. There are currently three projects on hydrogen-based steelmaking announced in the European Union. The Swedish steelmaking company SSAB runs the HYBRIT-project in cooperation with the Swedish iron ore provider LKAB and the Swedish energy supplier Vattenfall. The German Salzgitter started the SALCOS project, that

³⁵ Allwood, Julian M. (2016): A bright future for UK steel. A strategy for innovation and leadership through u-cycling and integration. University of Cambridge

³⁶ Voestalpine AG (2018): Pressemitteilung "voestalpine starts construction of the world's most advanced special steel plant in Kapfenberg, Austria". Available at: <http://www.voestalpine.com/group/en/media/press-releases/2018-04-24-voestalpine-starts-construction-of-the-worlds-most-advanced-special-steel-plant/>

focusses on the step-by-step transition of a current coal-based primary steelmaking site to primary steelmaking based on hydrogen based direct reduction using currently available technologies. Finally, the Austrian Voestalpine set up the H2Future/SuSteel project that aims at using H₂-plasma steelmaking. While Voestalpine and SSAB seem to need a longer time horizon for additional technology development, Salzgitter claims that it could start its transition to hydrogen during the 2020s only if the economic issues are solved, i.e. the higher capital and operational costs of hydrogen-based steelmaking compared to current coal-based steelmaking. Voestalpine is currently constructing a 6-MW-PEM in Linz, Austria, that aims at full scale demonstration of H₂ production with 1.200 m³ H₂ per hour and a project budget of 17.8 Mio EUR. The start is scheduled for 2021³⁷.

While SSAB and Salzgitter aim at using today's available direct reduction technology, Voestalpine chose plasma smelting reduction technology, a concept that has been discussed decades ago but that has not reached commercial availability³⁸.

Mitigation potential

If electricity is produced from renewable energy, the process can be close to CO₂-neutral steel production. It is estimated that CO₂-emissions can be reduced by 95% since carbon is still required for cathodes and since steel contains some carbon (less than 3%).

Costs and TRL

The economic viability of hydrogen-based steelmaking largely depends on the price of electricity and the price for CO₂. While SSAB, a Swedish steelmaking company, assumes that operation cost of hydrogen based steelmaking will increase by 20-30 % compared to current coal-based primary steelmaking (SSAB 2018), Voestalpine (an Austrian steelmaking company) finds that operational cost are likely to increase by 80 %³⁹. The direct reduction steelmaking based on hydrogen requires 3.48 MWh of electricity per tonne of liquid steel that is mainly consumed by the electrolyser for hydrogen production.⁴⁰ Total production costs are estimated between 361 to 640 EUR per tonne of steel depending on the electricity and CO₂ price, as well as the amount of scrap used. At electricity prices of 40 EUR/MWh and carbon prices in the range of 34 to 68 EUR per ton of CO₂, hydrogen-based steelmaking might become competitive with current coal based primary steelmaking.

1.2.4.3 Electrolysis of iron ore

Iron ore can directly be reduced to iron using the electrolysis process. This concept is being developed under the Siderwin-project funded by the European H2020 programme⁴¹. Alkaline electrolysis is used to produce direct reduced iron from iron ore using electrical energy thus replacing conventional blast furnaces and fossil

³⁷ Sormann, Axel (2018): CDA Steelmaking without carbon. K1MET, 22.02.2018, zuletzt geprüft am 17.10.2018.

³⁸ Chatterjee, Amit (1994): Beyond the blast furnace. Boca Raton, Ann Arbor, London, Tokyo: CRC Press.

³⁹ Kainersdorfer, Franz (2017): Dekarbonisierung der Stahlproduktion. Energiekonferenz „energy2050: Am Marktplatz Energiezukunft: Was wollen Kunden, was kann die Branche?“. Voestalpine, 27.09.2017.

⁴⁰ Vogl, Valentin; Åhman, Max; Nilsson; Lars J. (2018): Assessment of hydrogen direct reduction for fossil-free steelmaking. In: Journal of Cleaner Production (203), S. 736–745.

⁴¹ Siderwin (2018): Development of new methodologies for Industrial CO₂-free steel production by electrowinning. Online verfügbar unter <https://www.siderwin-spire.eu/>, zuletzt geprüft am 17.10.2018.

fuels in steel production. The reduction of the iron ore takes place at the cathode, while at the anode oxygen emerges as gas.⁴²

Mitigation potential

If electricity is produced from renewable energy, the process can be close to CO₂-neutral steel production.

Costs and TRL

Compared to commercial direct reduction plants that could use hydrogen from renewables to produce steel, this concept is currently under development (TRL 5-6). However, progress seems to be promising, since the construction of a demonstration plant with an annual capacity of about 130,000 tonnes is expected for 2030, while some years ago at the beginning of the Ulcos project (see below) its testing was still estimated for 2040 and beyond. Space requirements might be comparably high, but it is argued that the electrolysis cells can be put on top of each other. Also, the electrolysis works without carbon as a reducing agent, but steel requires some carbon. The electrolysis might be more energy efficient than steelmaking by hydrogen from renewables since the conversion of hydrogen from electricity is omitted.⁴³ It assumes for this technology a differential investment of approximately 200 €/t capacity compared to a conventional basic oxygen blast furnace.

⁴² Pardo, Nicolas; Moya, Jose Antonio (2013): Prospective scenarios on energy efficiency and CO₂ emissions in the European Iron & Steel industry. In: Energy 54, S. 113–128.

⁴³ M. Fishedick, J. Marzinkowski, P. Winzer, M. Weigel (2014): Techno-economic evaluation of innovative steel production technologies. Journal of Cleaner Production 84, 563–580.

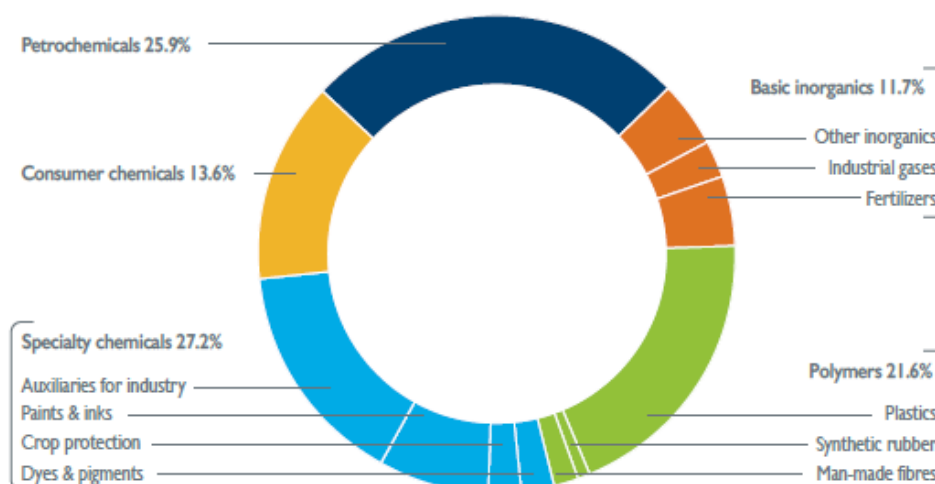
2 Chemicals

2.1 Core Products

The EU Chemical sector contributed approximately USD\$507 billion worth of sales in 2016, 15.1% of the global sales. Two chemical industries are responsible for the majority of the sectors emissions. The first deemed the “bulk chemicals” industry which includes chemicals such as ethylene dichloride, ethylene oxide and styrene, is based on the production of ethylene. It is responsible for 38,985 kt of CO₂ equivalent or 47% of chemical industry emissions. The second compound is ammonia which emits 23,396 kt of CO₂ equivalent, or 29% of emissions from the chemical industry. Together these industries are responsible for 76% of the sectors impact.⁴⁴

From a sales perspective, bulk chemicals do not contribute the majority of sales, but as precursors their influence is major. Below, the sales value shows how the petrochemical industry results in 25.9% of the chemical industry sales. This corresponds to the sales of chemicals directly related to Ethylene. However, the polymer industry uses petrochemicals as raw materials. As such, the combination of ethylene and ammonia directly affect 59.2% of the total sales value of the chemical industry. Consumer chemicals and speciality chemicals are very diverse; hence their production chain is difficult to track as a group. Base chemicals are nonetheless of use to these industries and can therefore be expected to influence these too.

Figure 2.1 EU chemical industry sales by sectoral breakdown⁴⁵



Ethylene and Ammonia together cover most of the emissions and sales value of the chemical industry. As such, this section focuses on these two products as representative of the chemical industry.

⁴⁴ European Union Transaction Log (EUTL), extracted July 2017

⁴⁵ Cefic Chemdata 2017

2.1.2 Ethylene⁴⁶

Ethylene (also known as Ethene) is a colourless flammable hydrocarbon gas. It has the chemical formula C_2H_4 . As a hydrocarbon it can be burned as a heat source. However, the value of ethylene lies in its molecular structure: $H_2C=CH_2$

The carbon atoms in the molecule are bonded with a double covalent bond. Most hydrocarbons are “saturated”, which means they are unable to accept any new hydrogens, methane (CH_4), for example, is saturated. Ethylene however, as it has a double bond, has the capability of breaking the extra bond to link with new atoms or molecules. It is therefore deemed “unsaturated”.

Therefore, not only does Ethylene have this very useful “unsaturated” feature which can allow it to react with many other chemicals, it also is the smallest possible unsaturated hydrocarbon. This allows chemists to use it as a building block to create all the chemicals described below.

2.1.3 Ethylene value chain

As described above, ethylene is the building block of the chemical industry, it allows the creation of many chemicals and as such is essential to the chemical industry. The following chemicals are its main products:

Ethylene oxide takes the form of a colourless gas at ambient temperature. It is utilised as a starting raw material to produce other sub-branches of intermediary products (Ethanol amines, ethylene glycol, ethylene glycol ethers, diethylene glycol), which is then utilised as feedstock material to produce finished products like food packaging, detergents, agrochemicals, coatings, adhesives, inks, detergents and pharmaceuticals.

Styrene takes the form of a clear colourless liquid which is mainly applied as raw material to produce other intermediary products: polystyrene, acrylonitrile-butadiene-styrene (ABS), styrene-acrylonitrile (SAN), styrene-butadiene rubber (SBR) and unsaturated polyester resins (UP resins). ABS is a tough, heat-resistant plastic widely utilised as housing for appliances such as consumer electronics, automotive components, luggage, sporting helmets and pipefittings. SAN is widely utilised to produce automotive components, electrical, electronic and building products. SBR is mainly utilised to produce tyres for the automotive industry. SBR is also applied to produce carpet backing, paper coating, belts, flooring, insulation material and footwear. Polystyrene is mainly utilised to produce single-use food packaging products.

Ethyl alcohol takes the form of a colourless liquid. It is also often classified as ethanol, grain alcohol or alcohol. It is applied to produce other intermediary chemical products such as ethyl acrylate, ethyl acetate and ethyl amines. These intermediary chemical products are utilised to produce solvents and finished goods such as coatings, adhesives, detergents, pharmaceutical, footwear, tyres and paper.

Ethylene dichloride takes the form of a colourless liquid. It is used mainly as a primary raw material to produce vinyl chloride monomer, which is consequently applied as raw material to manufacture Polyvinyl Chloride (PVC) plastics.

Polyethylene is the form of most common plastics utilised globally for packaging uses (plastic bags, plastic films, plastic bottles, etc.). It is a highly versatile synthetic

⁴⁶ Petrochemicals Europe, 2018

resin produced from the polymerisation process of ethylene. It can also be applied to produce synthetic fibres or rubber.

Acetaldehyde takes the form of a colourless liquid. It is applied as a starting material to produce intermediary products (acetic acid, vinyl acetate, plastics) which is then utilised to produce plastics.

2.1.4 Ammonia

Nitrogen Gas is composed of 2 nitrogen atoms (N_2), which are bonded together by a triple covalent bond. This bond is incredibly strong and makes dinitrogen gas very stable. As such, despite nitrogen being abundant in our atmosphere it is very difficult for it to be used in other chemicals.

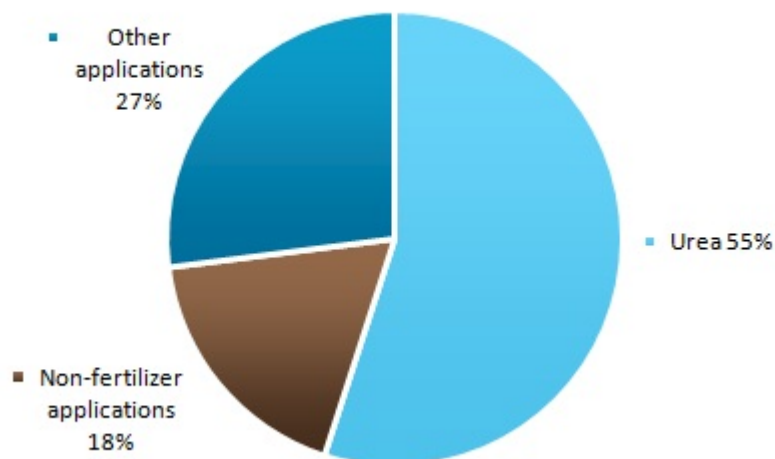
Ammonia (NH_3) takes the form a colourless gas with a distinct odour. The Haber-Bosch process, discovered in 1910, allows for nitrogen in the air to be captured and transformed into ammonia. This is a very energy intensive process but is worthwhile as the ammonia can then be used in agriculture as a nitrogen fertiliser. It enriches the soil in nitrogen which the plants can use to produce proteins and enable growth. Ammonia is the main building block for producing ammonia-based (ammonium nitrate) fertilizers. It is also a key component to many other household cleaning products.

2.1.5 Ammonia value chain

As illustrated in Figure 2.2, approximately 82% of global ammonia produced is used in fertilizer application to sustain agriculture production through soil fertilisation and increasing crop nutrients.

Figure 2.2 Global ammonia consumption by application in 2013⁴⁷

Global Ammonia Consumption by End Use Sector in 2013



⁴⁷ Ammonia: 2018 World Market Outlook, McGroun

The remaining 18% is used for industrial products, such as general surface cleaning solutions. Some newer applications under development for ammonia include its use as a refrigerant gas or for hydrogen storage.

2.2 Decarbonisation technologies

To provide visibility on decarbonisation options, the section will first study and elaborate on conventional manufacturing methods. This will provide a comparison baseline from which to evaluate other decarbonisation technologies. This baseline is compared with: (i) current Best Available Technologies (BAT); Carbon Capture and Storage (CCS) options; and (iii) novel decarbonisation technologies.

2.2.1 Ethylene

Ethylene is key to several chemical processes, most notable of which is plastics. As such it affects a multitude of manufacturing processes. Ammonia on the other side, is the keystone of modern agricultural practices.

Both of these industries have heavily engrained industrial processes, with a very high energy usage and carbon intensity. It is therefore crucial to review these manufacturing technologies and re-evaluate their production methods if we are to meet our carbon commitments and meet oncoming changes to the industry.

The decarbonisation options for ethylene are broadly categorised into 4 main categories:

1. **Business model innovation changes**, looking at how we source our raw materials and how we consume our plastics, by improving recycling tendencies and replacing ethylene with biodegradable materials;
2. **Process improvements** on our current manufacturing techniques, such as using catalysts to reduce energy consumption during production and improved chemical separation systems;
3. **Carbon capture storage systems** would allow the continuation of current manufacturing processes, but trap released gases from the process, allowing for reduced CO₂ emissions;
4. **Novel techniques** investigate new methods of ethylene production, e.g. ethylene from feedstocks such as methanol or converted CO₂, which is not commercially available in the market.

Table 2.1 and Table 2.2 present the summary of decarbonisation options for ethylene subsector.

Table 2.1 Technology readiness levels of selected mitigation options in the ethylene sub-sector

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency		Selective membrane filters		Catalytic naphtha cracking	
Fuel/Feedstock switch				Methanol to Ethylene production	
CCS and CCU	Ethylene CCS furnace				
Recycling and re-use					Plastic Recycling
Material efficiency (downstream)					
Material substitution		Plastic substitutes			

Table 2.2 Main characteristics of selected mitigation options ethylene sub-sector⁴⁸

Technology option	Examples	TRL	Max. emissions reductions ⁴⁹	Energy savings ⁵⁰	Market entry	Reference Technology
Catalytic cracking of naphtha	KRICT, LG, Asahi Kasei	8	Up to 20%	-20%	2020	Naphtha steam cracking
Low mechanical quality plastics replacements	PLA, PHA, PHB	6 - 9	Up to 11%	-11%	2015	Naphtha steam cracking
Plastics recycling	PET, HDPE	9	Up to 11%	-11%	1980s	Naphtha steam cracking
Methanol to ethylene production		8 - 9	Up to 47%	-47%		Naphtha steam cracking
Carbon capture and storage furnace		5 - 8	Up to 90%		2030+	Naphtha steam cracking

⁴⁸ ICIS Consulting; Dechema, 2017; Technology Roadmap: Energy and GHG reductions in the chemical industry via catalytic processes, 2013 IEA

⁴⁹ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

⁵⁰ Energy savings show the reduction in energy consumption resulting from the technology change

Technology option	Examples	TRL	Max. emissions reductions ⁴⁹	Energy savings ⁵⁰	Market entry	Reference Technology
H₂O and CO₂ conversion to ethylene		3 - 4	Up to 216% ⁵¹		2030+	Naphtha steam cracking
Selective membrane for organic filtering systems		6 - 7	Up to 10%	-5%	2020/2030	Naphtha steam cracking

2.2.1.2 Conventional ethylene production methods

The main commercial methods of producing ethylene is through steam cracking of a variety of hydrocarbon feedstock. In general, the process goes through three major steps:

- Cracking and quenching;
- Compression and drying;
- Separation (also known as fractioning).

The cracking process involves putting the hydrocarbon under high temperatures in a controlled, oxygen-free environment. This is typically done under a steam. This “cracks” hydrogen chains, either removing hydrogen atoms or breaking chains into smaller pieces. The resulting hydrocarbons will contain non-saturated hydrocarbons (or olefins), the main of which will be propylene and ethylene for a process under naphtha feedstock.

Compression and drying of the cracked gas are intended to remove impurities such as water, hydrogen sulphide and carbon dioxide. The product is then separated to isolate ethylene for sale.

Figure 2.3 shows the global feedstock production ratios for ethylene, mainly split between naphtha and ethane. In Europe, naphtha and ethane are the primary feedstock for Ethylene production. Nevertheless, LPG consist of approximately 25% of the feedstock and is gaining market importance in Europe. The utilisation of ethane feedstock undergoes a similar process to steam cracking of naphtha feedstock; however, this process only produces ethylene and no other High Value Chemicals (HVC). Production of ethylene with ethane feedstock is particularly prominent in North America given that ethane is significantly cheaper as a feedstock in comparison with other liquid hydrocarbon like naphtha. As the US production is expected to grow faster than the EU, the global ratio is predicted to shift slightly away from naphtha as feedstock.

⁵¹ This process has a CO₂ emission reduction above 100% as CO₂ is captured as feedstock to the production process. The feedstock needs surpass the CO₂ process emissions.

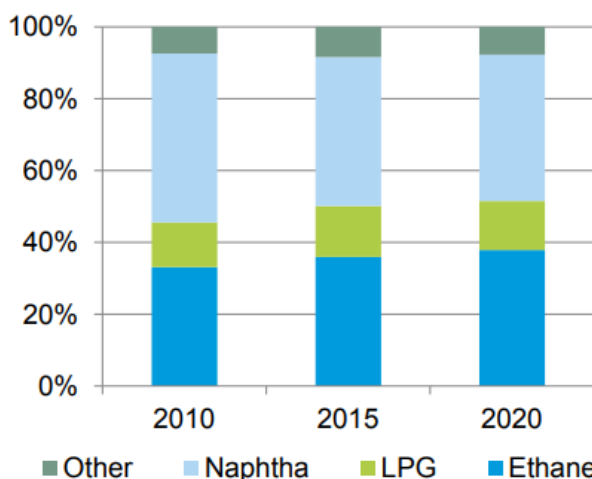


Figure 2.3 Global Ethylene production by feedstock⁵²

Figure 2.4 provides an overview of the ethylene production process through steam cracking of naphtha feedstock. Production of ethylene with naphtha feedstock also yields other High Value Chemicals (HVC), including propylene, C4 olefins and aromatics (ethyl benzene). Crackers are usually designed to take a variety of feedstock.

The naphtha feedstock is fed into a furnace, which undergoes a pyrolysis process (a thermal cracking of petroleum hydrocarbon with steam, also known as steam cracking). The feedstock hydrocarbon is pre-heated and diluted with steam, and further heated to its cracking temperature. Steam dilution lowers the hydrocarbon partial pressure, enhancing olefin yield as a result. Steam helps to lower coking deposits by reacting with coke to form carbon dioxide (CO₂), carbon monoxide (CO) and Hydrogen (H₂). The cracked products are cooled down immediately to preserve the gas composition and reduce the formation of secondary reactions (C₄, C₅, C₆, C₇, aromatics and heavier products).

The cooled down cracked gas is then compressed and dried before sent to the distillation columns. The drying process is typically carried out through chilling and adsorption on molecular sieves. Acid gasses (CO₂, H₂S, CO) are removed through a scrubber prior to the fractioning process.

The compressed dried cracked gas is fractioned at specified qualities through a series of distillation columns and hydrogenation reactors. Through this sequence of distillation columns, ethylene is refined by removing other components one by one: bigger molecules of 6 carbons first, then 5, 4, 3. Methane is then separated out of the mixture, the rendering gas is then composed only of hydrocarbons with only 2 carbons. Acetylene, ethane and ethylene are separated in turn. These other components can also be sold as high value chemicals, notably propylene, which is also used in many chemical synthesis processes.

This conventional Ethylene synthesis through naphtha cracking uses energy equivalent to the release of 0.76 tons of CO₂ per ton of ethylene produced.

⁵² ICIS Consulting

The diagram illustrates the process of Ethylene Production by Naphtha Cracking. The process begins with Naphtha storage, which feeds into a Feed pump. The pumped naphtha then enters a Furnace, where it is heated by High pressure steam. The heated naphtha then passes through a Heat exchanger and a Cooler before entering a Compressor. The compressed naphtha then enters a series of separators: C6 separator, C5 separator, C4 separator, and C3 separator. The C3 separator output goes to Acid gas removal, which produces CO, CO₂, and H₂S. The output of the C3 separator then enters a Demethanizer, which produces Hydrogen and Methane. The output of the Demethanizer then enters a CH₄ Separator, which produces CH₄ and H₂. The CH₄ and H₂ then enter a Hydrogenator, which produces Acetylene. The output of the Hydrogenator then enters a C2 splitter column, which produces Ethylene and Ethane. The Ethylene and Ethane then enter a Compressor and a Cooler before being sent to the final product storage. The diagram is watermarked with 'www.inclusive-science-engineering.com'.

2.2.1.3 Incremental CO2-reductions with BATs

- Optimization of heating coils;
- Integrated gas turbines with cracking furnace;
- Low grade waste heat recovery; and
- Advanced furnace material (ceramic fibres).

After cracking, product separation has the highest-energy cost in the production process. Cryogenic separation is currently the most adopted commercial process. However, new techniques exist, such as:

- 

Best available technologies include absorption separation process, which involves running a gas stream through a liquid in which the intend component is dissolved into the liquid. Adsorption separation is a similar process than the absorption, but instead of dissolving the component into a liquid, the gas is run through a solid powder, on which the desired chemical would deposit onto, hence separating the components from the gas stream. Selective membranes can also be used for separation as they can be designed to only allow certain gaseous molecules to go through them.

These technologies combined are estimated to bring energy costs of ethylene production to 12 GJ/t. The European industry has been very careful to keep production at high performance values, and the average energy consumption for ethylene production is now 12.2 GJ/t, whereas the world average is at 13.8 GJ/t.⁵³ Hence Europe can further diminish its ethylene energy footprint through BATs by 1.5%. Therefore, as the Ethylene industry currently emits 38,985kt of CO₂ equivalent, applying these BAT across the entire industry would save 585kt.

2.2.1.4 Decarbonisation with CCS

Following the same production method, Carbon Capture Storage (CCS) offers the potential to capture up to 90% of CO₂ emissions from power plants and industrial process emission. The CCS chain consist of three main stages: (i) Capturing of CO₂; (ii) transportation of CO₂ and (iii) Storing of CO₂ in a secure geological formation. Capturing the CO₂ essentially means to compress the gas into a sealed container. This usually also involves a separation process to extract the CO₂ from the flue gas (if capturing the CO₂ after combustion it would be mixed with air hence N₂, O₂ and water). Separation technologies include cryogenic process, solid or liquid absorption and selective membranes. Transport like any other gas can be done through compressed tanks or pipes. For storage of the carbon dioxide is injected into an underground geological formation (depleted oil or gas reservoirs are good candidates). Once injected, the carbon dioxide moves up through the storage site until it reaches an impermeable layer of rock (which cannot be penetrated by carbon dioxide) which traps it underground.

Ideally this process is useful for large industrial processes, producing lots of CO₂ at high concentration. This saves costs (and energy) for separating the CO₂. Geographical proximity to the storage site of course also a source of savings regarding CO₂ transport.

CCS can be done in three different methods:

- Pre-combustion capture; a process where the fuel (generally methane or coal) is reformed to hydrogen and CO₂, allowing the CO₂ to be stored and the hydrogen to be used as a fuel elsewhere. This process provides near 100% concentration CO₂ stream.
- Post-combustion capture; is a process where the fuel is burned in a classical fashion, but the resulting fumes are captured. The CO₂ is then extracted from the stream and stored.
- Oxy-fuel combustion system separates oxygen and nitrogen from the air, and feeds only oxygen into the combustion chamber. The resulting gases from combustion are then trapped and stored. This technique has an advantage over

⁵³ Dechema, 2017

the post-combustion capture, as the stream of gas created is much higher concentration of CO₂, and the fuel burns more efficiently.

For ethylene production, post-combustion and oxy-fuel are the most likely candidates. These can result in a saving of 0.684 tons of CO₂ equivalent per ton of Ethylene produced. We currently estimate CCS technologies plied to the cracking process to be at a technical readiness level of 5-8. The infrastructure costs for such a process is currently estimated between 500 and 1000 €/ annual tonnage capacity.

The ethylene manufacture process, however, offers opportunities for Carbon Capture and Utilisation, for CO₂ to be transformed into usable goods. Notably the catalytic creation of methanol from water and CO₂. The methanol can then be converted to ethylene as is detailed in the following section. This has the potential to capture 2.86 tons of CO₂ captured per ton of ethylene produced.

2.2.1.5 Decarbonisation with novel techniques

Catalyst enabled processes

Mitigation potential

The cracking reaction is highly endothermic (i.e. absorbs high amount of energy from its surrounding), and hence high energy usage is required. The cracking of hydrocarbon feedstock could be improved with catalyst technologies such as catalytic pyrolysis and catalytic partial oxidation. These have been used in demonstration plants and deliver a 20% energy savings to the cracking reaction. This saving would result in a total 7,797 kt of CO₂ equivalent avoided if applied across the entire EU ethylene industry.

Costs and TRL

Having already been shown to work in demonstration plants, the technology is at a high TRL of 8 as the first commercial catalytic cracking plant is now online in China. Depending on the catalyst used, the cost of such an installation is estimated between 100 and 500 € per tonnage annual capacity.

Application of technology

Using a catalyst in chemical reaction enables a reaction to occur easier but doesn't participate directly in the reaction. In this sense, the catalyst isn't consumed during the process. It does, however, enable a reaction to happen faster, more efficiently or favour one reaction compared to another possible reaction. For ethylene production, this means that a catalyst would allow for the cracking reaction to require lower temperatures and possibly at a faster rate, hence saving on energy. Another aspect to be wary of is that in the case of naphtha cracking, this could favour the production of ethylene. Depending on the client base, not producing other High Value Chemicals such as propylene or aromatics can be a commercial advantage or disadvantage. If pure ethylene is wanted, then such catalytic specialisation would also allow for energy savings with regards to separation columns.

Installing these catalysts would probably require for the cracking columns to be modified to be able to accommodate for the catalyst material. These are often metals, such as copper or titanium, and can therefore have their own associated costs. Although they do not participate directly in the chemical reaction, catalysts can be consumed during reaction, where side products such as coke may deposit

on their surface rendering them inactive. They therefore would require cycles to clean or refresh them to optimal performance rates.⁵⁴

Ethylene from ethanol dehydration

Mitigation potential

Ethylene can be produced by dehydrating ethanol. This method was used in the past before petrochemical means outstripped the performance of this biological source route. It requires much lower temperature than naphtha cracking. However, it isn't viewed as a method delivering carbon savings compared to conventional manufacturing due to market conditions. The cost of ethanol (bio or not) is higher than that of ethylene hence the commercial dynamics are not in place. One product of ethylene is ethanol.

Cost and TRL

Ethylene was originally produced from ethanol being passed through heated catalyst in the 18th century. The technology is therefore close to readiness if commercial conditions make it viable.

Application of technology

The technology is currently not viable under current commercial conditions. However, it is good to note that ethylene can be produced from sources other than fossil fuels. If biologically sourced ethanol were to flood the market, this technique could provide a source of ethylene at a relatively low carbon footprint. Not only can feedstock be sourced from biological sources, but as the reaction temperature is lower, the heat of reaction could be sourced from waste heat of other processes.

Steam from electricity

Mitigation potential

Another technique is simply to convert the water into steam for the cracking process through electrical heating rather than gas. Currently, this technique would be more carbon wasteful than heating through gas. However, as the EU grid is steadily converted to renewable sources, we could see by 2035 a situation where electric furnaces would be more carbon efficient than gas.

Cost and TRL

Electric boilers are not a new technology and hence can be expected to be at a TRL of 8, simply to review a method to incorporate the technique into the ethylene production steam. Costs can also be classified as negligible.

Application of technology

The technology would simply replace a water boiler powered by gas with one powered by electricity. This isn't a new technology but is only carbon effective if the electricity grid is less carbon intensive than burning gas. There would be a need for local grid infrastructure to be reinforced to carry the extra current capacity.

Ethylene production via low carbon Methanol-to-Olefins (MTO)

Mitigation potential

⁵⁴ Technology Roadmap: Energy and GHG reductions in the chemical industry via catalytic processes, 2013 IEA

Methanol is one of the largest volume chemicals in the world and serves as source for various other compounds. In Europe, methanol is predominately produced from natural gas via steam reforming, to a very small extent also from heavy oil. The alternative low-carbon pathway to methanol is based on hydrogen, produced by water electrolysis with low-carbon electricity, followed by hydrogenation of CO₂ as carbon source. The CO₂ footprint of the low-carbon methanol synthesis comprises two contributions: 1) the consumption of CO₂ as carbon feedstock and 2) the process related emissions, in this case predominately or exclusively caused by electricity, the latter in the case a full electrified concept including steam generation is enabled. The low carbon methanol then follows the established Methanol to Ethylene (MTO) production route to convert into ethylene. The MTO approach is 47% more efficient than synthesis of ethylene through Naphtha cracking, which can therefore account for savings if production is done through methanol, whether it comes from atmospheric CO₂ or simply biomass production. This process is nearly commercially feasible.

Considering the full cycle of water, CO₂ production of methanol to ethylene, the production would result in a net capture of 0.68 tons of CO₂ per ton of Ethylene produced, which would increase to 0.88 tons if the electricity supply were fully renewable.⁵⁵

Cost and TRL

The process to convert methanol to ethylene has already been demonstrated to function and has a TRL of 8. However, the production method from CO₂ capture to ethylene has yet to be demonstrated and has a TRL of only 3-4. Current costings for this technology have been estimated at higher than 1000 €/ton capacity

Application of technology

The advantages of this technology come in multiple aspects. As the feedstock can be from methanol (which can be derived from biological sources), or from captured CO₂, the technology is not bound to prices or taxes on fossil fuels. Of course, the aspect of capturing carbon can render this technology carbon negative. As ethylene is often feedstock to produce plastics, this would be a longer-term carbon trap (assuming the plastic isn't burned).

The technology would, however, require a completely new feedstock stream and reinvention of the industrial process. A steady stream of CO₂ or methanol would be required. The current industrial process could scarcely be used in this new process.

Artificial photosynthesis

Mitigation potential

Artificial photosynthesis uses sunlight to create high-value chemicals. The method has shown promise for direct hydrolysis producing H₂ gas, which as shown above can be converted to methanol and subsequently ethylene. It can also directly produce synthetic organic molecules, such as ethylene.

Cost and TRL

This research has shown results but is still in early research stages (TRL 2-3).

Application of technology

⁵⁵ Dechema 2017

Recent research has led to efficient light-absorbing semiconductors with high photo-electrochemical output and efficient catalysts to convert raw materials into a diverse range of products. The technology would require very low energy to run simply running on sunlight. However, the downside would mean that production cycles would be slow and linked to sunlight availability. Access to a CO₂ source would also be required.

This technology wouldn't leverage any of the existing infrastructure or technology of the ethylene industry.

New plastics divergence

A decarbonisation technique to be aware of is a shift away from ethylene demand. With concerns about material efficiency and circular economy aspects coming to the public eye, the move away from the "throwaway" plastic culture would reduce demand for ethylene. General recycling efforts and new sorting techniques would push demand for raw ethylene down. Beyond the waste concern of plastics, production of plastics from recycled material instead of raw ethylene uses approximately 50% less energy. At present, 30% of wasted plastics are recycled in the EU. Assuming this rate were to increase to 50% by 2050, the demand for raw ethylene would reduce by 8% simply from the recycling increase.

For high mechanical property materials, 3D printers are capable of creating these on demand, for plastics and other materials. Capable of producing tailored products, the demand for mass produced plastic objects may reduce in favour of specialised, high value, 3-D printed items. Most of these materials are not ethylene-based, which may shift demand away from ethylene production to other materials.

Due environmental concerns of plastics flooding the ocean, low mechanical property plastic products (such as plastic shopping bags), may shift away from low density polyethylene or polystyrene to biodegradable plastics. These are usually polylactic based, therefore diverting demand away from raw ethylene.

These technologies are already at commercialisation level and hence at high TRL. The shift away from ethylene would therefore be dependent solely on the commercial development of these other technologies.

Selective membranes

Mitigation potential

Selective membranes have been developed for many years in many different fields. Currently separation in industrial chemical systems are done mainly by distillation and fractioning techniques, which can be quite heat intensive. Using selective membranes would allow for chemical separation to be done at lower energy costs. The technology has been used for other similar chemical streams and is capable of delivering 5% energy savings to the ethylene industry.⁵⁶ This would result in a saving of 1,949 kt of CO₂ equivalent from current industry practice.

Cost and TRL

Selective membranes are developed in other areas. For example, they are commonly used in water treatment facilities, these filters can separate pure water

⁵⁶ Materials for Separation Technologies: Energy and Emission Reduction Opportunities, US department of Energy

from contaminants by allowing certain chemicals through but not others. Their TRL for ethylene applications is therefore estimated at 6-7. Current costings for such an application haven't been calculated.

Application of technology

These would require the chemicals to be brought at higher pressures, but no heat differential is required by the process as would be for fractional separation. These can be installed at the rear end of a classical ethylene production method, and hence only replacing the separation process. As such, they can be incorporated with relative ease into the infrastructure.

2.2.2 Ammonia

With regards to ammonia, the industry is currently aware of the potential need for a crucial restructure of their operations. Rather than simply produce fertiliser, agrochemical plants are looking at methods to optimise fertiliser delivery and tailor demand and production. We have identified below the initiatives with potential to decarbonise the industry for ammonia production. These fall into 2 main categories:

1. **Carbon capture storage systems** would allow to continue to current manufacturing processes, but trap released gases from the process, allowing for reduced CO₂ emissions;
2. **Novel manufacturing methods**, to create Hydrogen gas feedstock in novel methods from electricity rather than through methane steam reformation.

Table 2.3 and Table 2.4 presents the summary of decarbonisation options for ammonia subsector.

Table 2.3 Technology readiness levels of selected mitigation options in the ammonia sub-sector

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency					
Fuel/Feedstock switch			Alkaline electrolysis H ₂ production		
		Solid Electrolyte Membrane H ₂ production			
		PEM H ₂ production			
CCS and CCU		Ammonia CCS			
Recycling and re-use					
Material efficiency (downstream)					
Material substitution (downstream)					

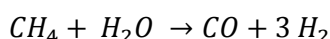
Table 2.4 Main characteristics of selected mitigation options ammonia sub-sector⁵⁷

Technology option	Examples	TRL	Max. emissions reductions ⁵⁸	Energy savings ⁵⁹	Market entry	Reference Technology
H2 production through Solid Electrolyte membrane electrolysis		6 - 7	Up to 75%	- 9%	2025	Methane steam reformation
H2 production through Proton Electrolyte Membrane electrolysis	Audi Werlte	7 - 8	Up to 75%	-8%	2015	Methane steam reformation
H2 production through Alkaline electrolysis	IHT, ELT	7 - 9	Up to 75%	-8%	2020	Methane steam reformation
Carbon capture and storage furnace		6 - 7	Up to 97%		2030+	Methane steam reformation

2.2.2.2 Conventional Ammonia production

Ammonia is almost exclusively produced in large scale plants (up to 3,300 t/day). In Europe, the most common feedstock is natural gas and it is produced through the Haber-Bosch⁶⁰ process. CO₂ is formed as a by-product of the production process, directly from the synthesis process and indirectly from the consumption of fossil fuel-based heat source throughout the production process. Figure 2.5 illustrates the typical production process through ammonia synthesis with hydrogen and nitrogen.⁶¹

The process relies on two chemicals, Nitrogen gas (N₂) which is 80% of breathable air, and Hydrogen (H₂). The Nitrogen is obtained from the air, Hydrogen, however, is usually produced from methane steam reformation. This consists of heating (700 – 1100°C) methane with steam in an oxygen free environment with a catalyst (typically Nickel). This controlled reaction creates CO and H₂, as shown below:



This reaction is endothermic (requires heat to be input) and hence very energy intensive. The process can be further optimised by running the gas stream into a

⁵⁷ Dechema, 2017; Cefic, European Chemistry for growth, 2013; Institute for Industrial Productivity; Solid-state electrochemical synthesis of ammonia: A review, journal of Solid state electrochemistry, 2011

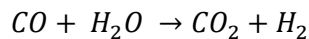
⁵⁸ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

⁵⁹ Energy savings show the reduction in energy consumption resulting from the technology change

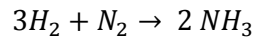
⁶⁰ Method of directly synthesizing ammonia from hydrogen and nitrogen, developed by German chemist Fritz Haber.

⁶¹ Dechema, 2017

lower temperature chamber with a copper catalyst, favouring the following exothermic reaction:

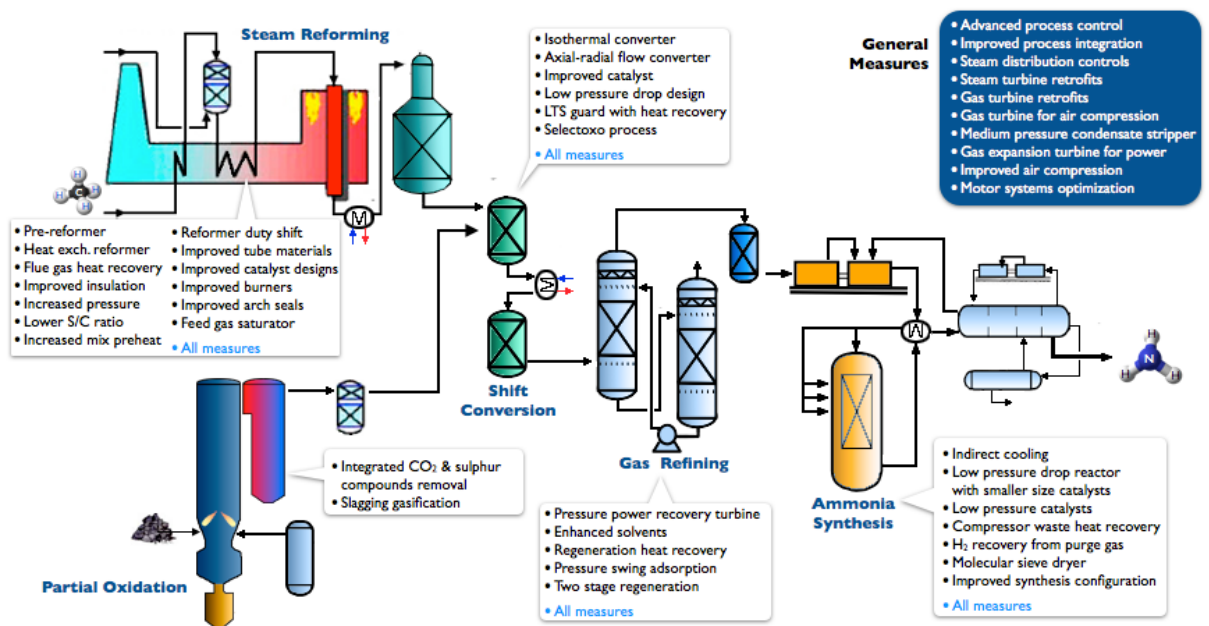


The hydrogen and nitrogen gas are combined at high pressure and temperature (400 - 500°C). Under catalyst conditions the Haber-Bosch reaction will occur as follows:



This conventional ammonia synthesis through methane cracking uses energy equivalent to the release of 1.83 tons of CO₂ per ton of ammonia produced, 1.33 tons of which are created during the hydrogen production.⁶²

Figure 2.5 Ammonia production process and the possible energy saving measures⁶³



2.2.2.3 Incremental CO₂-reductions with BATs

Many of the BATs for Ammonia synthesis can be carried across from ethylene production. The chemical reactions can be favoured through better catalysts and the furnaces themselves can be improved, with the following technologies:

- Optimization of heating coils;
- Integrated gas turbines with furnace;
- Low grade waste heat recovery; and
- Advanced furnace material (ceramic fibres).

Heating coils can once again be optimized, either from their gas heating system or upgraded to fully electric heating. As high temperatures are crucial for the Haber-Bosch process, any energy saving on these coils can make for large savings on the entire process. To optimise the process, the furnace can be insulated with higher quality insulation, retaining more heat during the process, and hence requiring less

⁶² Dechema 2017

⁶³ Institute for Industrial Productivity

energy to maintain at high temperatures. Not only can the heat be more efficiently generated and transmitted to the furnace, waste heat can be reused to provide energy to an integrated turbine generating electricity or used for heating buildings.

Current European plants consume 35 GJ / t ammonia, where the BAT would result in production as low as 32 GJ / t ammonia.⁶⁴ Hence Europe can further diminish its ethylene energy footprint through BATs by 8.6%. Therefore, as the Ammonia industry currently emits 23,396kt of CO₂ equivalent, applying these BAT across the entire industry would save 2,012kt of CO₂ yearly.

2.2.2.4 Decarbonisation with CCS

Just as with ethylene production, Carbon Capture Storage (CCS) offers the potential to capture emitted CO₂. This can be done through pre-combustion, post-combustion and oxy-fuel combustion capture. The process for ammonia can result in a reduction in emissions of 96%. This is higher than that of ethylene as one of the steps of ammonia production is methane steam reformation. This is a pre-combustion capture of CO₂, with a high CO₂ content. Other processes such as steel and cement, are traditionally only at 30% CO₂ composition. As the CCS process energy consumption is based on the volume of gas stored, CCS on ammonia waste stream would be very efficient. This technology is also at a TRL of 5-8 and an estimated capex estimated at 200 €/ annual tonnage capacity.

2.2.2.5 Decarbonisation with Novel techniques

Low carbon Hydrogen through electrolysis

Mitigation potential

As 72.7% of the energy for the process is consumed by the hydrogen production stage, the most carbon effective methods target this area. As such the production of H₂ can be produced through electrolysis, the process of splitting water molecules into H₂ and O₂. The two main techniques to achieve this is through alkaline electrolysis or Proton Exchange Membrane (PEM) reverse fuel cell electrolysis. Both of these techniques use only electricity as an energy source and require 11% less energy than the steam cracking process, which means an 8% reduction in the total ammonia production process. These would therefore save 1872 kt of CO₂ equivalent from current production technologies.

A Solid electrolyte membrane electrolysis is another method in development (currently at TRL 6). It can deliver a 12% better energy efficiency compared to methane steam reformation. This results as a 9% saving across the entire ammonia production chain. These fuel cells have shown prototype effectiveness but are reliant on a high temperature to enable high conductivity rates with the solid electrolyte. These would therefore save 2,106 kt of CO₂ equivalent from current production technologies.

If the electrolysis were powered by renewable electricity, this would reduce total ammonia production chain carbon by 75%, which amounts to 17,547 kT of CO₂ saved.

Cost and TRL

⁶⁴ Cefic, European Chemistry for growth, 2013

Both alkaline and PEM electrolysis methods are near commercialisation (TRL 7-9) but are still developing methods to ramp up production and cut capital costs, mainly focusing on improving catalysts in electrodes and electrolyte ion conductivity. Electrolyte membrane still require development and are at TRL of 6-7.

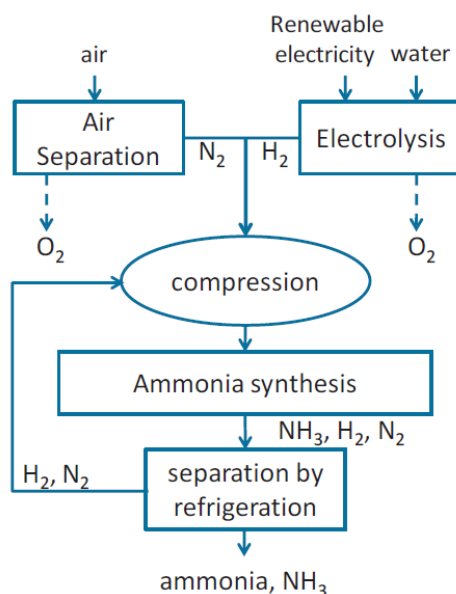
Application of technology

All of these technologies would need access to purified water for electrolysis. Being powered by electricity, a stable supply would need to be established too, which could require grid infrastructure reinforcements. More importantly, this process would replace entirely the methane reformation technology, a potential loss of investment and skill for industrials. Hydrogen and oxygen gases are both produced during electrolysis and a step would need to be added to separate the two.

Alkaline electrolysis has already been developed. However, relying on alkaline media, it is vulnerable to CO₂, which would block the electrolyte. As such, a PEM electrolysis is more favourable, capable of working in open atmosphere. Care must be taken to avoid electrodes from drying / flooding, but as the technology develops these effects are being addressed.

Solid electrolyte membranes do not have an issue with flooding or atmospheric interference, allowing for more stable rates of reaction. However, to have favourable rates of reaction, the solid electrolyte must be at high temperatures, requiring the infrastructure in place to keep the system at that temperature.

Figure 2.6 Low carbon ammonia production method⁶⁵



Photocatalysis of water

Mitigation potential

Another method in development is through photocatalytic materials. The concept is to create a material which when placed under water and under sunlight, will spontaneously electrolyse water, creating hydrogen gas and oxygen gas. Compared

⁶⁵ Dechema, 2017

to methane cracking, this method saves 99.6% of energy, with a spare 0.4% for gas handling costs such as compression.

Cost and TRL

The materials have been shown to work in laboratory trials but has yet to be tried into a prototype (TRL 2-3). Costings have yet to be estimated for this technique.

Application of technology

These materials would need a source of clean water, and sunshine. This makes the production rates directly reliant on the weather, which isn't reliable for industrial processes. This technology is compatible with Haber-Bosch process.

The gases of hydrogen and oxygen would be produced together. These would need an extra step to be separated. Furthermore, care must be taken to keep hydrogen away from a spark as it can ignite.

Solid state fuel cell production

Rather than create Ammonia through sheer thermal pressure of the Haber-Bosch process, solid-state fuel cells have been identified as a potential ammonia production method. The concept relies on a reverse fuel cell, using a proton exchange membrane, or an oxygen carrier. For a proton exchange membrane, the reaction requires a steady stream of Hydrogen gas on the anode and Nitrogen gas on the cathode. An applied electric potential will force hydrogen atoms to travel through the membrane and recombine with Nitrogen in the same reaction as that from the Haber-Bosch process. Oxygen carrier membranes would require a stream of steam and nitrogen gas on the cathode. The applied potential would dissociate the water, forming as products ammonia on the cathode and O₂ on the anode.

Both of these processes are still being researched. They require research to optimise catalysts and electrolytes to enable faster conversion rates and more efficient processes. Oxygen carrier electrolytes would be advantageous as the hydrogen production process wouldn't be required. In principle as the reaction is driven by directly forcing electrons off from Nitrogen, rather than forcing hydrogen and nitrogen together through heat and pressure, the reaction is expected to be a more energy efficient process. It would, however, still require a steady stream of hydrogen gas to be provided. As such, assuming all electricity provided were renewable, this technology would only be able to provide a total of 25% carbon savings compared to the conventional manufacturing method.⁶⁶

Ammonia consumption reduction

Another aspect to be aware of is the reduction in usage of ammonia. There is an expectation that usage from farming will be reduced from more targeted and controlled fertilising. Along this line of thought, circular economy aspects are likely to increase the fertiliser use of animal farming waste, community compost and biomass digestate. This sort of development may favour the development of smaller, innovative ammonia production plants, capable of responding to varying fertiliser needs.

⁶⁶ Solid-state electrochemical synthesis of ammonia: A review, journal of Solid state electrochemistry, 2011

3 Non-metallic minerals

3.1 Core Products

The EU ETS shows how the Non-metallic mineral industry is the most carbon intensive industry in the EU, producing 180,683 kT of CO₂e in 2015. This is ahead of the Iron and steel industry and petroleum refineries at 139,204 kT CO₂e and 125,977 kT CO₂e, respectively. The sectors main emitter is cement, producing 63% of the emissions. The remaining emissions are split between Lime (17%), Glass (10%) and Ceramics (9%) production, which respectively are responsible for 30,868 kT CO₂e, 17,940 kT CO₂e and 15,671 kT CO₂e.⁶⁷

3.1.1 Cement and Lime

Cement, and thus its major type, i.e. Ordinary Portland cement, is one of the most manufactured materials in the world. Cement is primarily used in the construction and geotechnical sector (buildings, bridges, tunnels, dams, etc.), but there are also emerging applications, such as water filtration^{68,69,70}.

Trends in Asian cement production dominate global cement production (Figure 3.1). In 2014, Asia holds a share of 80% of global cement production. Between 2004 and 2014, cement production in this region increased by 225% - mainly driven by China - while in Europe cement production decreased by 85% from 2004 levels during the same period. However, in 2014, Europe was still the third largest cement supplier (5.9%) behind America (6.7%). Africa has also doubled its cement production during this period, but on a much lower level. In 2014, cement production in Africa makes up only 5% of the global cement production. CIS and former Soviet countries also show increased cement production, i.e. by 154% between 2004 and 2014. In total, global cement production doubled (192%) between 2004 and 2014. Excluding trends in Asia, global cement production would have increased by 121% in that period.

In October 2018, the World Cement Association (WCA) presented an outline of its Climate Action Plan. The plan covers five areas including the optimal use of cement products in construction and exploring the potential of innovative technologies (WSA & GCCF, 2018)⁷¹.

⁶⁷ European Union Transaction Log (EUTL), extracted July 2017

⁶⁸ Maddalena, R.; Roberts, J. J.; Hamilton, A. (2018): Can Portland cement be replaced by low-carbon alternative materials? A study on thermal properties and carbon emissions of innovative cements. In: *Journal of Cleaner Production*.

⁶⁹ IEA; WBCSD (2009): Cement Technology Roadmap 2009. Carbon emissions reductions up to 2050. International Energy Agency; World Business Council for Sustainable Development, Cement Sustainability Initiative.

⁷⁰ WBCSD (2018): Sustainability Benefits of Concrete. World Business Council for Sustainable Development, Cement Sustainability Initiative.

⁷¹ World Cement Association and Global Climate Forum (2018): The World Cement Association Climate Action Plan. Online available at: <http://www.worldcementassociation.org/sustainability/the-wca-climate-action-plan>

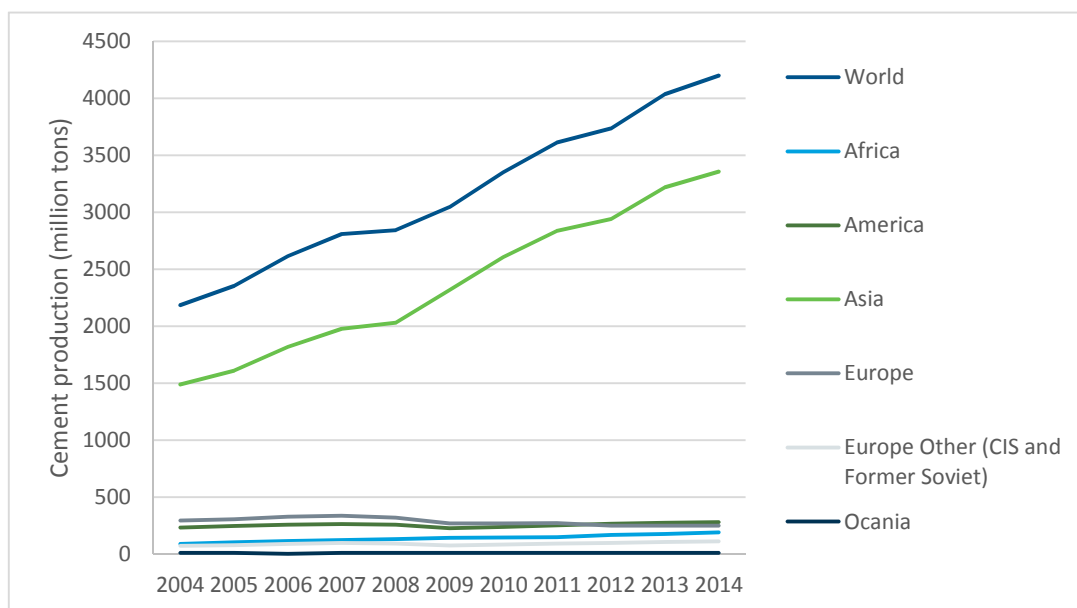


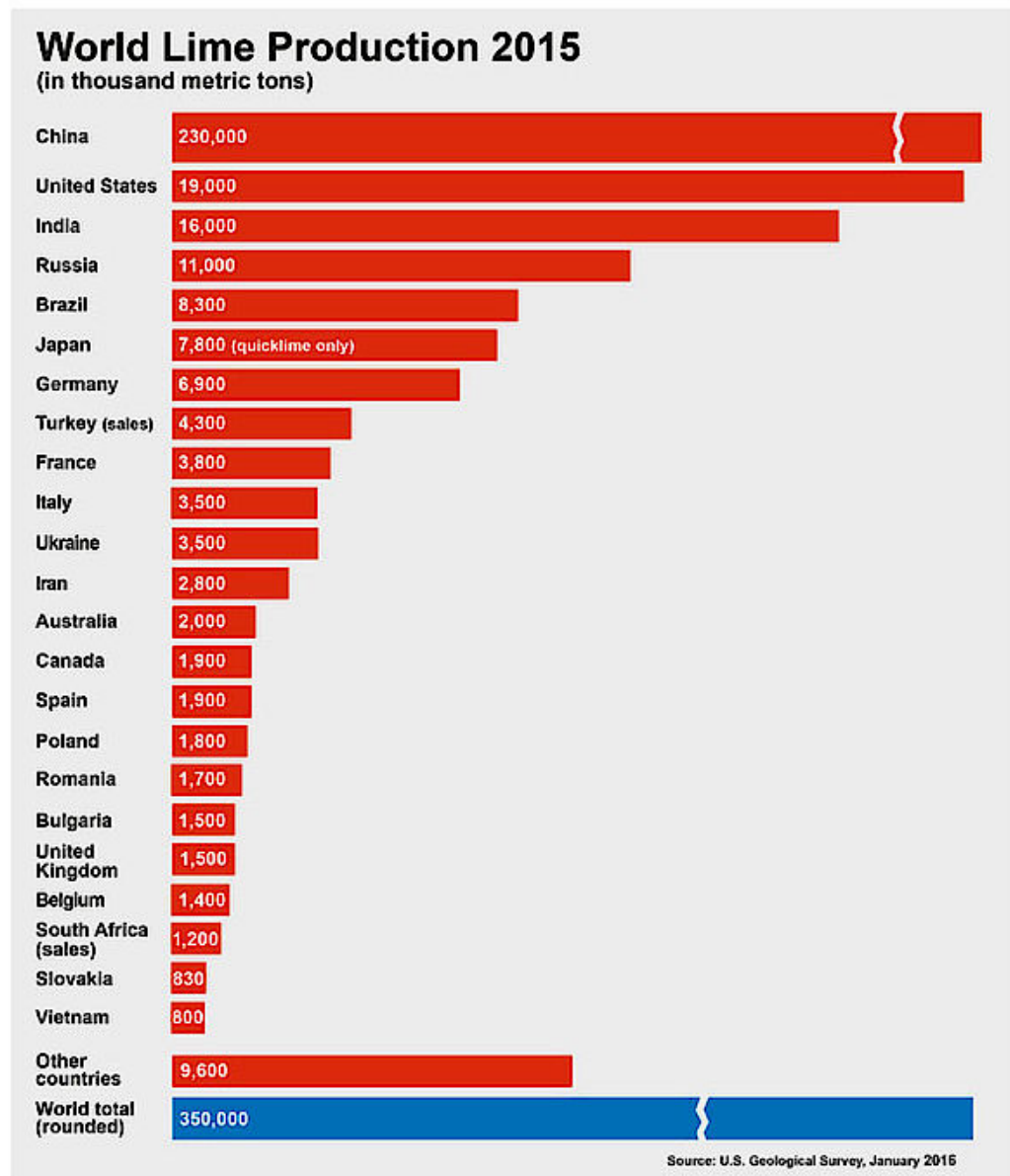
Figure 3.1 Global cement production by region 2004 - 2014⁷²

Lime production in China also dominates global production (Figure 3.2), with more than half of global lime production (65.7%) in 2015. The United States are the second largest lime producer, with a share of 5.4%. The BRICS countries (excluding China) supply 10.4 %, while European countries hold a share of 7.1 % of global lime production. Global lime production increased by 2.9 % (from 340 to 350 million tons) between 2012 and 2015.

Under the scope of the European Emission Trading System, the cement and lime sectors accounted for about 8% of total greenhouse gas (GHG) emissions in 2016 and about 28% of the industrial sector emissions within the ETS (see Figure 3.3). In 2016, CO₂ emissions in the EU cement industry were about 112 Mt, while they were at about 30 Mt in the lime industry. The cement industry accounts for around 40% of all energy use in the non-metallic minerals sector.

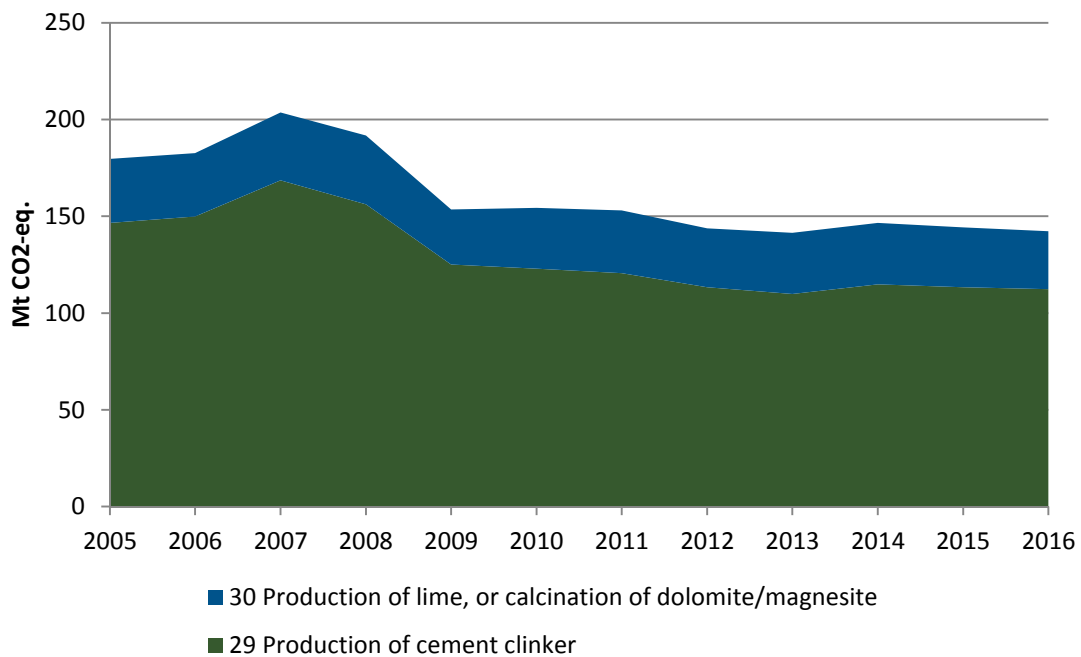
⁷² Cembureau, 2017

Figure 3.2 Global lime production by country 2015⁷³



⁷³ ILA 2018

Figure 3.3 Verified historical emissions for the EU28 cement and lime sector as reported in the EU ETS⁷⁴



Cement production has three primary steps. The first step is the mining, grinding and homogenisation of raw materials. Then, the energy intensive step of burning limestone (mainly CaCO_3) to calcium oxide (CaO) releasing CO_2 takes place in a rotary kiln. Clinker is a mixture of calcium oxide, silica, alumina, and ferrous oxides, that all originate from limestone. During the final step, the clinker is ground together with gypsum and other additives to produce cement⁷⁵.

The cement sector, compared with other sectors like steel, is more diversely structured. The ten largest cement companies hold a share of 31.6 % of global cement production in 2015 (Figure 3.4), while the rest is produced by a large amount of smaller companies.

Cement plants are typically sized to supply local demand due to its comparably low value to weight ratio. Indeed, cement is typically produced and consumed locally within a range up to 200 to 300 kilometres. But bulk transportation by ship enables imports and exports over longer distances. It is estimated that transportation costs from 10 Euro per tonne of cement over 100 km by road, and to 20 € per tonne of cement for crossing the Mediterranean Sea by ship including loading and unloading. Of course, prices for the transportation by ship are only valid for large volumes, i.e. in the range of 35.000 tonnes⁷⁶.

Thus, cement plants in those parts of the world that are within an economically viable range of a seaport might face international competition. BCG (2013) estimated that in 2012, 60 % of European clinker and cement production were located within less than 200 kilometres from coasts or inland ports. Countries that

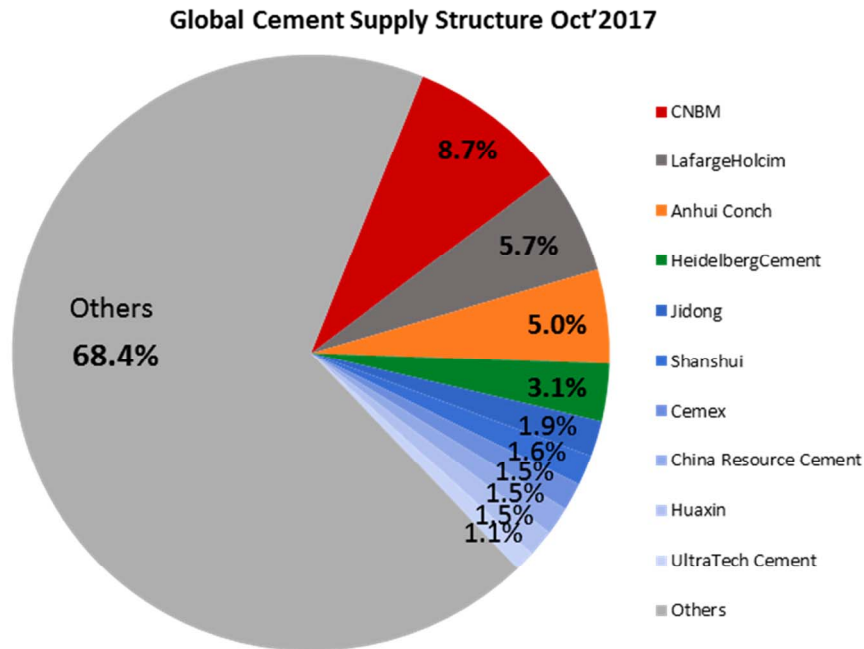
⁷⁴ EEA (2017)

⁷⁵ Pardo et al. 2011

⁷⁶ Cembureau 2018

export cement to Europe include China, Thailand, Colombia, Venezuela and Northern Africa.⁷⁷

Figure 3.4 Global cement supply structure by company October 2017⁷⁸



3.1.2 Ceramics⁷⁹

The ceramics industry includes multiple categories of sub-products⁸⁰:

- Bricks and roof tiles: use in the construction industry.
- Wall & floor tiles: indoor (buildings) and outdoor environments.
- Table- and ornamental ware: manufacturing kitchen and household goods, e.g. plates, dishes, cups, bowls jugs and vases.
- Refractories: a vital element in all high-temperature processes, such as metals making, the production of cement, glass and ceramics, and petrochemical processes. The main end user is steel industry (55.6%), followed by cement and lime industries (17.8%).
- Sanitary ware: high quality products tailored to the specific requirements of end consumers; e.g. s toilets, sinks, cisterns and bidets.
- Technical ceramics: a wide range of strategic applications. Examples include improvements in security (e.g. crash/airbag sensors, fire protection, and military protection); improvements in health (e.g. prostheses, pacemakers, cochlear implants); improvements for the environment (filter systems, e.g. catalytic converters, high pressure fuel injection, thermostats, insulation).

⁷⁷ BCG (2013): The Cement Sector. A Strategic Contributor to Europe's Future. Hg. v. Boston Consulting Group

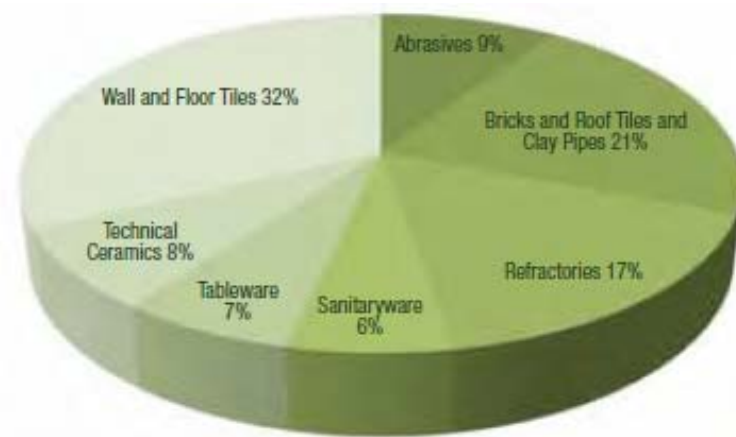
⁷⁸ World Cement Association 2018

⁷⁹ Study on energy efficiency and energy saving potential. ICF 2015

⁸⁰ Cerame-Unie

- Abrasives: a wide range of applications from industry (car, machinery, energy, air & space, shipyard, wood working, glass) to construction and consumer markets (DIY). Four types of abrasives products include: Bonded abrasives (ceramic and organic), Coated (cloth, paper), Super abrasives (Diamond and CBN) and Grains.
- Clay pipes: used for sewage and drainage purposes.

Figure 3.5 Ceramic product value chain⁸¹



3.1.3 Glass⁸²

The glass sector comprises five subsectors covering different products, applications and markets.⁸³

- Container glass (60% of the EU glass production): a wide range of glass packaging products for food and beverages as well as flacons for perfumery, cosmetics and pharmacy.
- Building, automotive, solar-energy glass (flat glass) (30%): the building (windows and facades) and automotive industries (windcreens, side and rear-side glazing, backlights and sunroofs). Flat glass is also used in solar-energy applications (photovoltaic and solar thermal panels) as well as in urban and domestic furniture, appliances, mirrors and greenhouses.
- Continuous-filament glass fibre: applications ranging from the automotive and transportation sector (such as aircrafts) to wind energy, agriculture, construction, communication, electrical and electronic as well as sport and leisure.
- Domestic glass (4%): glass tableware, cookware and decorative items such as drinking glasses, bowls, plates, cookware, vases and ornaments.
- Special glass (2%): a large range of products such as lighting glass, glass tubes, laboratory glassware, glass ceramics, heat-resistant glass, optical and ophthalmic glass, extra thin glass for the electronics industry (e.g. LCD panels, photovoltaics) and radiation protection glasses.

⁸¹ Cerame-Unie; 2013

⁸² Study on energy efficiency and energy saving potential. ICF 2015

⁸³ Glass Alliance Europe

3.2 Decarbonisation technologies

3.2.1 Cement and Lime

There are two main sources of CO₂ emissions in the cement and lime industry, i.e. process and energy related emissions. Energy related emissions from the burning of fossil fuels in the clinker/lime furnace are less than 0.5 t CO₂ / t clinker while the process related emissions from the decarbonation of the limestone are in the order of 0.52 t CO₂/t clinker.

Current mitigation efforts based on best available technologies (BAT) directly reduce CO₂ emissions by improving the energy efficiency of the production process and switching from fossil to renewable fuels. CO₂ emissions are indirectly reduced by substituting clinker with so called secondary cementitious materials like fly ash from coal fired power plants or slag from coal based primary steelmaking. With ambitious climate policies, however, the availability of such materials decreases.

While BAT options show further, but limited potential to reduce CO₂ emissions in cement production, additional mitigation options need to be explored. These include the CO₂-efficient use of cement along the entire value chain, better circularity and the development of new low-carbon cements.

Various low-carbon cements are currently under development. They are all based on different concepts. Several aim for a market introduction in the coming years with TRLs ranging from 7 to 9. However, long and costly certification procedures for new binders and a conservative construction industry could slow down their market introduction⁸⁴. . Novel cements need to fulfil the characteristics of OPC, even when this might not be necessary. Carbonation of concrete is the process through which atmospheric CO₂ seeps into the material. It is an issue for reinforced concrete, as it acidifies the concrete, removing the alkaline protection from oxidation the concrete offers the encased steel. When steel rusts inside the concrete, it loses its mechanical properties reinforcing the concrete, but also expands, developing cracks in the steel, further weakening the material. The reinforced concrete makes up about 25% of concrete applications⁸⁵. The idea of a "general purpose cement" reduces complexity for those who deal with it, like suppliers and consumers. However, this concept can be a serious barrier for the development and diffusion of novel cements, since it requires most of the cements to be carbonation resistant, while only a small share of them must protect steel from corrosion.⁸⁶

Research is ongoing into improved recycling options of concrete. For example, there is a concept based on electrodynamic fragmentation that aims to recycle demolition waste to a raw material suitable for cement production (whereas today's concrete recycling is mainly a form of downgrading).

Carbon-fibre reinforced concrete is another innovation with huge CO₂ mitigation potential. That is, if steel in construction is replaced by carbon fibres, the effects of carbonation do not affect the material, hence less cement is needed to attain the same strength and durability.

⁸⁴ Dewald und Achternbosch 2015

⁸⁵ Lehne und Preston, 2018. *Making concrete change: innovation in Low-carbon cement and concrete*

⁸⁶ Scrivener et al. 2018

Carbon capture and storage is a potential mitigation option for large cement plants and pilot projects are ongoing. Post-combustion seems the most advanced technology allowing market introduction soon.

The TRL-levels of the investigated mitigation options are presented in Table 3.1; Table 3.2 shows the main characteristics of selected mitigation options.

Table 3.1 Technology readiness levels (TRL) selected mitigation options in the cement and lime sector

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency			Low-carbon cement 50%	Low-carbon cement 30% Low-carbon cement 70%	
Fuel switch					
CCS and CCU	Direct separation (lime)	Oxyfuel CCS	Post combustion CCS		
Recycling and re-use		Cement from recycled concrete	Design for disassembly		
Material efficiency (downstream)	CO2-efficient material use				
Material substitution (downstream)			carbon reinforced concrete		

Table 3.2 Main characteristics of selected mitigation options cement & lime industry⁸⁷

Technology option	TRL	Max. emissions reductions ⁸⁸	Energy savings ⁸⁹	Market entry	Reference Technology
Low carbon cement 30% (e.g. Aether)	8-9	up to 30%	~15%	<2020	Ordinary Portland Cement
Low carbon cement 50% (e.g. Celitement)	7	up to 50%	30-40%	2020	Ordinary Portland Cement

⁸⁷ IEA; WBCSD (2009): Cement Technology Roadmap 2009. Carbon emissions reductions up to 2050. International Energy Agency; World Business Council for Sustainable Development, Cement Sustainability Initiative; CEN, 2000 ; Imbabi et al. 2012; Brunke et al. (2014); VDZ, 2012; CSI and ECRA 2017; Vincent et al. (2016); Public LEILAC pre-FEED summary report; Gartner, EM; Sui, T. (2017); Aether (2018); Lehne, J. et al. (2018); Meyer, V. et al. (2016); Scrivener et al. (2018); Gehring, F. et al (2015)

⁸⁸ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

⁸⁹ Energy savings show the reduction in energy consumption resulting from the technology change

Technology option	TRL	Max. emissions reductions ⁸⁸	Energy savings ⁸⁹	Market entry	Reference Technology
Low carbon cement 70% (e.g. Solidia)	8-9	up to 70%	~20%	<2020	Ordinary Portland Cement
Recycling of concrete	7			2025+	Ordinary Portland Cement
Carbon reinforced concrete	7-8			2020	Steel reinforced cement

3.2.1.2 Current production process

Cement is a mixture of finely granulated clinker and other additives, such as granulated slag, fly ash, lime and gypsum. Clinker is the core ingredient of cements and the most energy-intensive one. It is burned to pellets from limestone and clay in a rotary kiln at temperatures of 1,450 °C⁹⁰.

The most widely used cement type is Ordinary Portland Cement (OPC), which contains up to 95% cement clinker⁹¹. In 2016, nearly 4.65 billion metric tons were produced globally (Cembureau). Other types of cement use a variety of clinker substitutes, including granulated blast-furnace slag, fly ash and natural pozzolana, in blends with Portland cement to reduce CO₂ emissions. These clinker substitutes have properties similar to cement and can therefore be added to the feedstock for a kiln or substituted for clinker in either the cement or concrete mix⁹². Ordinary Portland Cement is generally made from around 80% limestone and 20% clay.

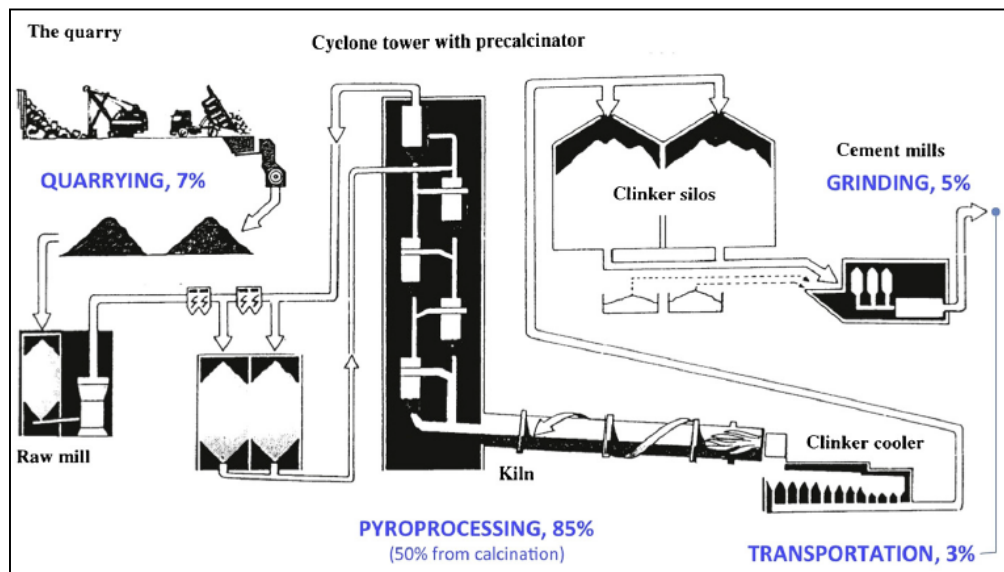
Two main sources of CO₂ emissions are important in the cement and lime industry: First, the emissions from the burning of fossil fuels in the clinker/lime furnace (< 0.5 tCO₂/t clinker depending on energy efficiency and fuel mix) and, second, process related emissions from the decarbonation of the limestone (~0.52 tCO₂/t clinker). Together these two sources make up about 85 % of total CO₂ emissions of the entire Portland Cement production value chain from quarrying to distribution (Figure 3.6).

⁹⁰ Imbabi, Mohammed S.; Carrigan, Collette; McKenna, Sean (2012): Trends and developments in green cement and concrete technology. In: *International Journal of Sustainable Built Environment* (1), S. 194–216

⁹¹ IEA; WBCSD (2009): Cement Technology Roadmap 2009. Carbon emissions reductions up to 2050. International Energy Agency; World Business Council for Sustainable Development, Cement Sustainability Initiative

⁹² CEN, 2000

Figure 3.6 Process steps of Portland Cement production and associated CO₂ emissions by process step⁹³



Roughly, cement production includes three process steps: quarrying or the raw materials, pyro processing (i.e. burning of limestone and additives to pellets), and grinding of the pellets to cement (Figure 3.6).

Cement production begins with quarrying of the raw material, i.e. limestone. Typically, cement plants are located close to limestone quarries. The raw materials are milled together to achieve the right composition before further processing. Then the raw material is burnt in a rotary kiln, a large industrial oven that turns around once or twice every minute. The process temperature is about 1400-1600°C. Finally, the clinker is ground with additives such as gypsum to produce cement.

Cement manufacturing is highly capital intensive. The lifetime of cement kilns ranges up to 30 or 50 years. New kilns are typically built in growing markets, e.g. in Asia, Eastern Europe and Africa. Still, cement kilns are continuously being modernized. Major parts of the equipment (e.g. preheater cyclones, clinker cooler, burner, etc.) are often replaced with modern technology after 20 to 30 years. Thus, even rather old kilns, e.g. in Europe, can be comparably efficient⁹⁴.

3.2.1.3 Incremental CO₂ reduction through best available technologies

Today's mitigation efforts concentrate on three main pillars. These include

- improving energy efficiency,
- switching to low-carbon/renewable fuels, and
- reducing the clinker content in the cement by using e.g. fly ash or blast furnace slag.

⁹³ Imbabi et al. 2012

⁹⁴ Brunke, Jean-Christian; Blesl, Markus (2014) : Energy conservation measures for the German cement industry and their ability to compensate for rising energy-related production costs. In: *Journal of Cleaner Production* 82, p94-111

Improving energy efficiency

Current best available technology (BAT) for the cement industry is a dry-process kiln with pre-heater and precalciner. Implementing BAT on the cement production process is likely to achieve limited efficiency and CO₂ savings in the coming decades, because no energy efficiency technology is available that allows reducing process-related emissions (besides reducing clinker content in cement).

The thermodynamic minimum energy required to drive the endothermic reactions is approximately 1.8 GJ/t clinker for dry limestone feedstock. In practice, it is much higher, as feedstocks contain significant moisture. The practical BAT level of thermal energy demand of a six-stage pre-heater and pre-calciner kiln is estimated to be in the range of 3.0 GJ/t in the case of six cyclone stages⁹⁵. The Research Institute of the Cement Industry in Germany carried out a study that determined the ranges for the yearly average fuel energy requirement of state-of-the-art cement kilns based on empirical data⁹⁶. These data show a decreasing energy consumption with increasing number of cyclone stages:

- Three cyclone stages: 3.4-3.8 GJ/t clinker
- Four cyclone stages: 3.2-3.6 GJ/t clinker
- Five cyclone stages: 3.1-3.5 GJ/t clinker
- Six cyclone stages: 3.0-3.4 GJ/t clinker

Best available technologies for electricity consumption in the cement industry depends on the type of plant, but typically range from 95 kWh/t to 100 kWh/t cement. The increased use of alternative fuels, however, tends to increase electricity demand for pre-treatment and handling.

To summarize, the remaining thermal efficiency potential until 2050 is estimated to be less than 10%⁹⁷. Thus, breakthrough technologies are essential to achieve an 80% CO₂ reduction target by 2050 compared to 1990.

Alternative fuel use

The use of alternative fuels, such as waste, in the cement industry is a well-established practice in many countries since it reduces production costs. Additionally, CO₂ emissions are reduced if alternative fuels such as waste products are used that would otherwise have been incinerated or land filled. The high process temperatures in cement production and the cleaning function of clinker and limestone facilitate waste combustion. Hence, used tyres, wood, plastics, chemicals, treated municipal solid waste and other types of waste are co-combusted in cement kilns in large quantities.

The use of waste fuels in the European cement industry increased from 3% in 1990 to 15% in 2005. Cement producers in Austria, the Czech Republic, France, Germany, Belgium and the Netherlands have reached substitution rates of between, 7% and more than 43% of the total energy used during this time horizon. Some individual plants have achieved nearly 100% substitution using alternative fuels. The use of alternative fuels at high substitution rates requires tailored pre-treatment and surveillance systems. In Europe, the burning of alternative fuels in cement kilns is

⁹⁵ European Commission, 2010

⁹⁶ VDZ, 2012

⁹⁷ CSI; ECRA (2017): Development of State of the Art Techniques in Cement Manufacturing Trying to look ahead. Cement Sustainability Initiative; European Cement Research Academy. Dusseldorf, Geneva

covered by the Directive 2000/76/EC of the European Parliament and Council, which aims to prevent or to limit the negative effects on the environment, and the resulting risks to human health, from the incineration of waste.

Besides waste, biomass can also be an alternative fuel with a high potential to decrease CO₂ emissions. In the future, also electric furnaces can be an option, although, currently, they are not optimised for the industrial scale.

3.2.1.4 Decarbonisation with CCS

CCS Post combustion - oxyfuel - pre-combustion - carbon looping

Due to the high specific CO₂ emissions of cement plants, CCS is a potential mitigation technology for the cement industry. There are various designs feasible including post combustion, oxyfuel process, pre-combustion and carbon looping. Each option shows several advantages and disadvantages and have reached different levels of maturity. While for post combustion, a few pilot and demonstration plants have been implemented, oxyfuel and carbon looping technologies are still immature and require more R&D investment. The oxyfuel technology uses pure oxygen instead of air in the combustion chamber combined with flue gas recirculation, which increases the CO₂ concentration of the flue gas substantially. The principle has been proven in lab scale tests and currently a pilot plant is prepared by ECRA. Its implementation is expected for 2020. Pre-combustion is less attractive for the cement production, because it does not allow capturing the process related emissions from the carbonation of limestone.⁹⁸

CCS direct separation

A CCS technology specifically adjusted for cement and lime production is currently being developed by the EU Horizon 2020 project LEILAC. Its core technology is based on direct separation, which separates the calcination of the limestone from the combustion of fuels and, thus, generates a pure stream of CO₂ emissions. Compared to other CO₂ capture technologies (oxyfuel or post-combustion), this technology has the advantage that it does not require large amounts of additional energy for the CO₂ capture. A pilot plant, within an existing cement plant in Belgium, is planned within the LEILAC project. Results of the pilot testing phase are expected for 2020. While the technology is proven for magnesium oxide, it is estimated as TRL5 for lime and cement⁹⁹.

Carbon capture and use (CCU)

Carbon capture and use (CCU) is today less developed and researched than carbon capture and storage (CCS). There are various possibilities for the use of CO₂ including enhanced oil/gas recovery, mineral recarbonation, raw material production for the synthesis of chemical products in combination with hydrogen, growing of algae, etc. To assess the effectiveness of such CCU options, it will be important to understand the lifetime of the resulting products to determine how long the CO₂ can be stored. For long-term mitigation, many CCU options require CO₂ capture at some point along the lifecycle in order to circulate the CO₂ and avoid emissions

⁹⁸ CSI and ECRA 2017

⁹⁹ Vincent, Adam; Rennie, Daniel; Soeats, Mark; Gill, Matthew; Thomsen, Simon (2016): Public LEILAC pre-FEED summary report.

after product end-of-life. An exception is CO₂ absorbing concrete (such as Solidia cement), which captures ambient CO₂ during curing or during lifetime and even stores the CO₂ after the infrastructure is demolished.

3.2.1.5 Decarbonisation with Novel techniques

New binders are developed to replace conventional Ordinary Portland cement (OPC) and thus reduce CO₂-emissions. Different types of new binder concepts are under research and development. They differ in process specifications as well as raw material use.

Replacing raw materials and thus reducing the share of limestone in the input mix is an effective way of reducing process related emissions. However, since cement is consumed in large quantities, also its raw materials need to be largely available at reasonable prices. Alternative raw materials, such as magnesite lack sufficient availability or must be preserved to produce nutrients as in the case of phosphor. Making use of the calcium content in seawater is not viable since research has indicated that it would result in the vast production of hazardous chlorides¹⁰⁰. Next to limestone, an alternative raw material could be magnesium silicates, but so far, there is no energy-efficient process at an industrial scale available. As such, most of the approaches to mitigate CO₂ emissions still rely on the consumption of limestone.

There are several activities focused on the development of low-carbon cements; however, not many projects to test the novel concepts.

In the following, selected examples of new binders are discussed. They are not grouped according to material composition as often done; instead, they are grouped according to the potential CO₂ mitigation effect. The reference technology is Ordinary Portland Cement (OPC).

Low carbon cement (-30%)

A type of binder that contains more alumina, e.g. so called belite-yehelemite-ferrite, uses 20-30% less limestone resulting in CO₂ emissions reductions in roughly that range.

Mitigation potential

One example of this class of binder is Aether that requires less limestone but consumes more aluminium sources instead. Thus, CO₂ emissions are reduced, but costs increase since aluminium-rich sources are more expensive¹⁰¹. Additionally, the clinker production temperature reduces from 1450°C to about 1300 °C. However, higher raw material costs could be offset by an increase in productivity since less energy is needed. This new type of clinker is also said to be easier to grind thus reducing associated energy demand. The clinker burning can take place in existing rotary kilns used to produce Ordinary Portland Cements, though the kilns may need some adaptation. In total, CO₂ emissions could be reduced by 25-30%.

Costs and TRL

Currently the focus is to identify the most appropriate market segments and to develop this low-carbon-cement for specific niche applications that justify the

¹⁰⁰ Gartner, EM; Sui, T. (2017): Alternative cement clinkers

¹⁰¹ Scrivener, K I; John, V.M; Gartner, E.M (2018): Eco-efficient cements: potential economically viable solutions for a low-CO₂ cement-based materials industry

additional costs. However, for the long term the aim is to provide an alternative to Ordinary Portland Cement suitable for a wide range of applications¹⁰². The TRL is estimated to 8-9.

Low carbon cement (-50%)

There is at least one project that aims to develop the core binding component of cement, i.e. calcium-silicate-hydrate, using a process that consumes less limestone and thus might reduce CO₂ emissions by 50%¹⁰³.

Mitigation potential

One of these concepts, Celitement, is based on calcium hydrosilicates that harden after mixing with water through the formation of calcium silicate hydrates. Celitement is produced in a two-stage process that requires temperatures of about 200°C that is far below the temperature level of Ordinary Portland Cement production (i.e. 1450 °C). It aims to replace OPC. The new binder can be produced from quicklime (i.e. a product made from limestone) and sand. Compared to the production of Portland cement, less lime and energy is required, resulting in overall CO₂ reductions during production of up to 50%. However, despite the reported CO₂-savings, various researchers (e.g. (Lehne und Preston 2018), Scrivener et al. 2018 and (Gartner und Sui 2017) claim that Celitement's overall CO₂-emissions are much lower and that they are comparable to those of belite rich Portland Cements (that emit just 10% less CO₂ than OPC).

Costs and TRL

Currently, a pilot plant produces 100 kg per day of the new binder in Karlsruhe and a commercial plant with a capacity of about 50,000 t/a will be ready in 2019. The TRL is estimated to be 7.

Low carbon cement (-70%)

A core element of cements, i.e. calcium silicate, may also harden in the atmosphere by carbonation, instead of water-based hydration.

This type of cements captures CO₂ during curing (carbonation curing). One concept, Solidia, is produced with the same raw materials as Ordinary Portland Cement in existing cement kilns, but at lower kiln burning temperatures and using less limestone (Solidia Technologies, 2018). Solidia uses low-lime calcium silicate minerals such as wollstonite to produce calcium silicate clinkers (CCSC). This results in about 30% lower CO₂ emissions during cement production. Additionally, the concrete curing process takes place in special curing chambers at 40-60°C and at high concentrations of CO₂.¹⁰⁴ Thus, the curing process captures up to 300 kg (or 30%) of CO₂ per ton of cement used. The curing chambers enable fast hardening within about one day. However, the curing in special chambers can limit cement applications to pre-cast concrete elements (Solid Life Project 2018), which represent only a small share of the cement market. Solidia is also not suited for reinforcing steel, since the cement does not protect steel against corrosion.

¹⁰² Aether (2018): Aether low carbon cements

¹⁰³ Lehne, J.; Preston, F. (2018): Making concrete change. Innovation in low-carbon cement and concrete. Chatham house, London

¹⁰⁴ Meyer, V.; Gimenez, M. (2016): LafargeHolcim's activities, CCS/U and low CO₂ cements, focus on Solidia Technologies

Mitigation potential

Combined the production of the new binder and of the CO₂ absorbing concrete could reduce CO₂ emissions up to 70%, compared to OPC products.

Costs and TRL

The TRL is estimated at 8 to 9, as industrial demonstration has taken place in 2014 (Solid Life Project 2018). The economic viability of Solidia depends on the CO₂ price and whether a circular economy for CO₂ develops, i.e. that CO₂ from industrial processes can be supplied at low prices.

Low carbon cements (<-90%)

Cements produced from basic magnesium silicate rocks might also be an option. These rocks, that are globally abundant contain no chemically bound CO₂. Additionally, the cements could be cured with CO₂ if enough magnesium carbonate forms in the resulting hardened binder. Yet there is so far no industrial process for making magnesium oxide from natural basic magnesium silicates in an energy-efficient way. Novacem, a UK based company, aimed at developing an industrial process for manufacturing such cements from basic magnesium silicate rocks, but went bankrupt in 2012. The use of these binders has not yet been proven, although Novacem tested these on a small scale. According to (Gartner und Sui 2017) these binders might create very low, or even carbon-negative cements in the long-term. However, since no company is investing in this concept anymore, public funding may be required to support its development.¹⁰⁵ The TRL is estimated to below 5.

Additional options

New binders based on calcined clays and limestone fillers are both promising raw material substitutes. First, they show an abundant availability and second, research results report high mitigation potentials. However, the TRL is at 4-5.

3.2.1.6 Decarbonisation technologies - Circular economy and material efficiency

The current use pattern of cement presents high potentials for more efficient material use and unexploited circularity across the value chain. In the following, some promising research and development directions are discussed.

CO₂-efficient use of cement in the construction sector

Cement and concrete are low cost products used vastly in today's construction sector. Manifold opportunities to reduce concrete and cement use are available, however, mostly not exploited due to their low price. Approaches include, the more efficient use of concrete considering the purpose of the structure (including its service life) and, the optimal concrete mix design.

As the cement and concrete price, however, does not reflect the CO₂ emissions that occurred during production, the cement and concrete are not used efficiently. Besides price incentives, improved CO₂ efficiency also requires objective quantitative methods for measurement of the CO₂ impact. For instance (Haist et al. 2016) propose a method for the quantification of the sustainability of concrete on the

¹⁰⁵ Scrivener, K I; John, V.M; Gartner, E.M (2018): Eco-efficient cements: potential economically viable solutions for a low-CO₂ cement-based materials industry

material level considering service life, performance, durability and global warming potential, among others. Such an approach would allow consumers to select/design a low-carbon concrete specifically for the purpose needed. Furthermore, they compare the applicability of concrete mix designs containing less than 10% cement (ultra-low cement concretes). While they find promising mechanical properties and very high CO₂ reduction potentials, the long-term durability is often not yet sufficiently strong. Hence, more research on concrete designs is required. Furthermore, a regulatory framework for the CO₂-efficient use of cement will be mandatory for a successful market diffusion of low carbon concretes.

Recycling of concrete

Concrete is recycled in various ways. Demolition waste is currently mostly recycled to aggregates for use in road sub-base, a lower-quality application¹⁰⁶. Recycled concrete can also replace sand in concrete up to a certain share. However, this might be more CO₂-intensive than using virgin materials. Recycling of demolition waste is energy-intensive, and it might require decontamination. Recycled materials may also increase cement demand since they can reduce the concrete's strength thus leading to an increase in CO₂-emissions. Through its energy-intensive transportation it is important to recycle and use concrete locally¹⁰⁷.

Through electrodynamic fragmentation, demolition waste can non-destructively be separated into gravel, sand and lime. The concept was developed by Fraunhofer, Leibniz and Schwenk and uses ultrashort, underwater electrical discharges. The gravel can then be reused in concrete. However, this concept is energy intensive due to the electrical discharges as well as through the transportation and by the necessity to put the demolition waste under water for its treatment. Therefore, the environmental impact of this concept is only favourable over primary production¹⁰⁸ in certain cases. The TRL is estimated to be 7.

Recycling of concrete may also result in the recovery of non-carbonated calcium oxides (CaO) that can be used as raw material in clinker production. Using recovered concrete as raw material to produce new cement is under research but might have a high potential to reduce CO₂-emissions related to limestone use.

While CO₂ is emitted during cement production, crushed concrete (e.g. in demolition waste) carbonates, can absorb CO₂. This potential has been studied e.g. by (Engelsen et al. 2005) or (Possan et al. 2017). Even though (Scrivener et al. 2018) supports that the CO₂-absorption of cement-based materials can be considered a natural form of carbon capture and storage, she also puts forward that the carbonation is not included in the CO₂-balance of cement making since the carbonation rate is very slow.

Carbon reinforced concrete

Today, concrete is reinforced with steel mainly in construction appliances. While concrete resists pressure forces, steel allows for pulling forces. The concrete additionally protects the steel from corrosion. If the steel is replaced with a non-

¹⁰⁶ Lehne, J.; Preston, F. (2018): Making concrete change. Innovation in low-carbon cement and concrete. Chatham house, London

¹⁰⁷ Scrivener, K I; John, V.M; Gartner, E.M (2018): Eco-efficient cements: potential economically viable solutions for a low-CO₂ cement-based materials industry

¹⁰⁸ Gehring, F. et al (2015): Aus Altbeton wird Beton – ein innovativer Recyclingansatz

corrosive material, e.g. carbon, then the concrete layer may be thinner. The project carbon composite concrete (C3) from Dresden, Germany, develops carbon reinforced concrete, in which the steel reinforcement is substituted by carbon nano-fibres. Such composite materials allow much more efficient construction and might even reduce concrete consumption of up to eight times compared to steel reinforced concrete. For instance, walls of carbon reinforced concrete can be built with a thickness of 2 to 3 centimetres, while current steel reinforced walls have a thickness of 7 to 8 centimetres (Interview).

The project also evaluates the recycling of carbon reinforced concrete at the end of its lifetime. From a technical perspective, its recycling is possible. Economically the recycling will depend on future prices. Currently, 15-20 projects have been implemented in different market segments. The TRL for recycling carbon concrete is thus estimated to 7-8.

Costs and TRL

Up to 20% of current steel reinforced concrete appliances can be replaced with carbon reinforced concrete in an economic way (e.g. maintenance of bridges). While carbon concrete is still more expensive than traditional steel reinforced concrete, it becomes economically competitive by the much lower quantity needed. Even more, thinner walls result in gains for living space, which also is an economic advantage in densely populated urban areas.

However, various barriers still prevent a quick market diffusion. For example, since carbon reinforced concrete is much thinner than current steel reinforced concrete appliances, construction workers will need to change their routines and work more precisely. Given the fact that the work routines related to traditional concrete have been established over decades, change is slow. In addition, knowledge transfer is an important factor. Architects and civil engineers need training on how to design and how to build with carbon reinforced concrete.

Additional options

- Improved building insulation cements that save energy. An example is the mineral foam Airium.
- Nano engineering of concrete for high durability and strengths is still at TRL 3-4¹⁰⁹.
- If old building components could be re-used in new buildings, new cement production could decrease. However, those elements would have to be reassembled without destroying them (Design for disassembly).

3.2.2 Ceramics

The ceramics industry produces a variety of materials from construction materials in bricks and tiles, home furnishings to high performance technical materials.

The decarbonisation options for such a varied group of materials can be split into three main categories:

1. **Alternative fuels**, which rely on the current manufacturing processes but are powered by renewable sources, such as biomethane.

¹⁰⁹ Abdolhosseini Qomi et al. (2014): Combinatorial molecular optimization of cement hydrates. In: *Nature communications* 5, p.4960

2. **Carbon capture storage systems**, which allow the continuation of current manufacturing processes, but capture released gases from the process; and
3. **Circular economy techniques** investigate methods to recycle and reuse ceramics.

3.2.2.1 Conventional production process

The production of ceramics can be generally categorised into five main stages:

Raw materials preparation. The production process starts off with the preparation of numerous raw materials. These processes include crushing, hammering, batching (measure and weighing), mixing and grinding, screening, atomisation, separation and filtering processes.

Forming. The forming process shapes up the final product and includes both dry and wet methods. Forming processes include die forming, dry pressing, extrusion, punching and moulding.

Drying and treatment. The ceramic products go through a drying process immediately after forming, especially for wet method forming. This process may take up to several days to ensure all moisture is removed to prevent shrinkage cracks. The drying methods include tunnel dryers, infrared lamps, impulse burners and microwave drying. Where applicable, supplementary treatments are applied after drying; glazing, engobing and other treatments (metallisation, burning-out, pre-firing, hot pressing, hot isostatic pressing). This step accounts for approximately 26% of the total CO₂ emissions of the production process.

Firing. The ceramic product undergoes an intense heating process to strengthen the product to its desired porosity. The products are heated up in a kiln with a typical temperature range of 800°C – 1,800°C. The firing process may take up to several days. Most of the kilns are heated by gas burning. The firing process could take place in a classic tunnel kiln (most common), fast firing tunnel kiln, roller kiln and shuttle kiln. Temperature ranges for refractory materials are as follows:

- Fireclay bricks 1250 - 1500 °C
- Silica bricks 1450 - 1500 °C
- High alumina bricks 1500 - 1800 °C
- Magnesite bricks 1400 - 1800 °C

Temperatures for technical ceramics:

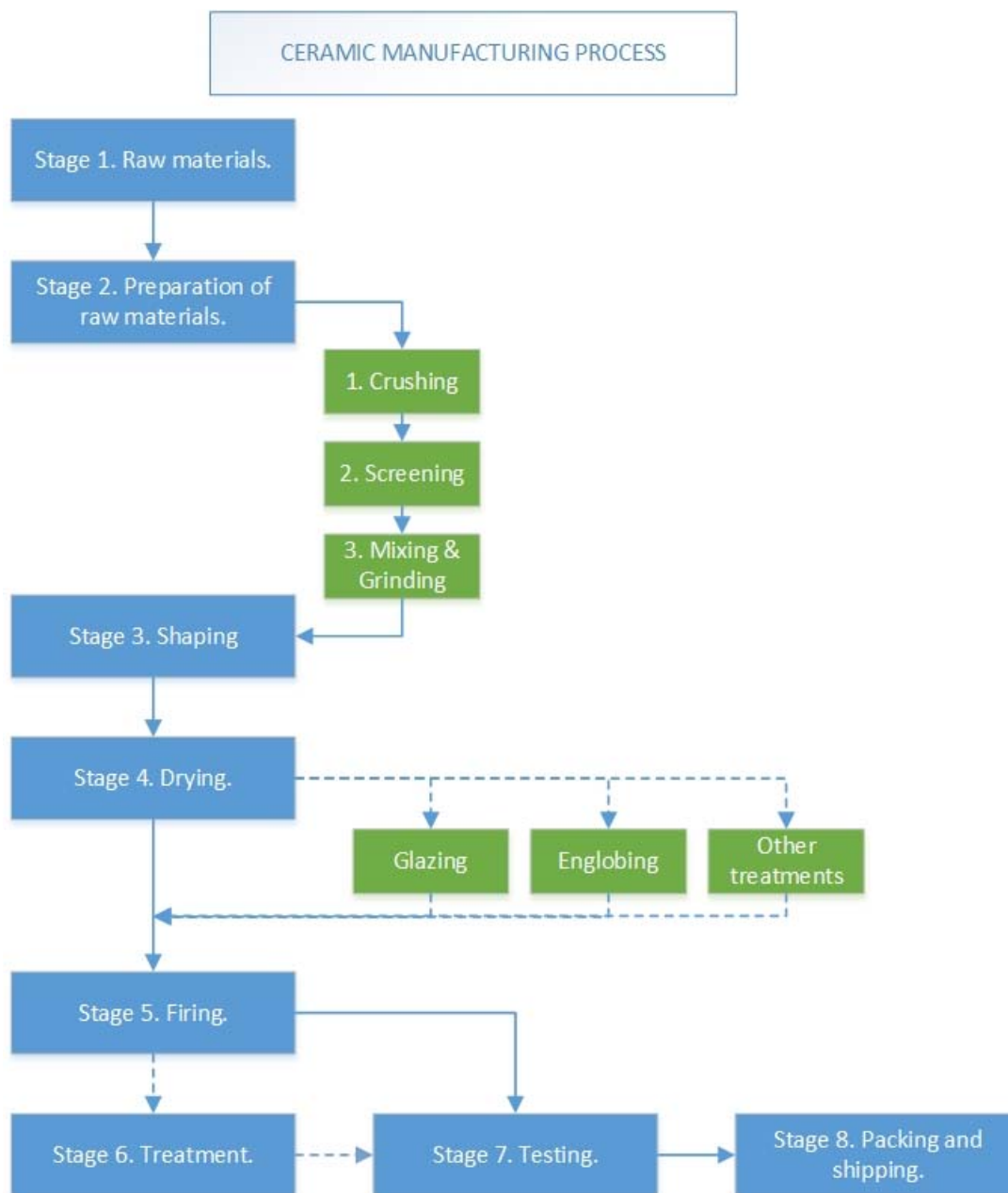
- Alumina porcelain: 1250 °C
- Quartz porcelain: 1300 °C
- Steatite: 1300 °C
- Cordierite: 1250 °C. – 1350 °C
- Aluminium oxide: 1600 °C. – 1800 °C
- Recrystallized silicon carbide: 2300 °C. – 2500 °C
- Sintered silicon carbide: 1900 °C
- Silicon nitride: 1700 °C

This step is the most energy intensive of the production process and accounts for 57% of the total CO₂ emissions.¹¹⁰

¹¹⁰ CO₂ emission calculation and reduction options in ceramics tile manufacture- The Foshan Case, Junxia Peng, Energy Procedia 16 (2012)

Downstream processes. The downstream processes are usually related to the products finishing and quality; testing, quality checks, grinding, sawing, cutting and others. The final processes are not energy/carbon intensive.

Figure 3.7 Cermaic manufacturing process chart



As illustrated in Figure 3.7, the specifics regarding material composition and firing temperatures will change for different ceramic products. As such, the carbon footprint will vary according to the product. As tiles are the majority product in the ceramics industry, we will focus on the carbon footprint associated to its production. Based on UK 2012 production, ceramics produce the equivalent of 0.29 tons of CO₂

per ton of ceramic produced.¹¹¹ As described in the opening section, the EU ceramics industry emissions were at a total of 15,671 kT CO₂e.¹¹²

Incremental CO₂-reductions through BATs of the ceramics sub-sector is mainly centred around the drying and firing process. Savings can also be reduced through raw materials optimisation.

Optimisation of raw materials delivers energy savings through two main means: new materials, and waste recovery. Low thermal mass materials and ceramic fibres have reduced energy consumption by using new ceramic formulas requiring less heat during the firing process (up to 20% of energy savings). Material recovery such as sludge recycling, re-use from other industries, unmixed raw material feedback and broken ware feedback, allow for energy savings as they reduce the requirements for raw material preparation.

Taking nearly 30% of the manufacturing energy requirements, ceramics drying can be optimised through integration with firing kiln design. Typically, these technologies can allow for a 10% reduction in drying costs. Rather than using convective heat, the ceramics can also be dried through radiation technologies. These are more efficient as the energy can be directed to the ceramic pieces, minimizing waste heat to environment. Depending on the ceramic end product (notably its thickness), Infrared or microwave radiation are used and can result in up to 50% reduction in energy use for the drying process.

The firing process can be optimised using electronic controls (for pulse burners), waste heat recovery and better insulation materials, reducing radiant and convective heat losses. As this step can account for 57% of the total energy process, optimisation is often focused in this sphere. Radiant and convective losses can be reduced by up to 60% through BATs.

Considering the current application of BATs, it is estimated that full uptake of BATs across the EU could reduce energy usage by 17%, saving 2,664kT CO₂e.¹¹³

3.2.2.2 Decarbonisation through CCS

Carbon Capture Storage (CCS) is potentially a solution for the ceramic industry. The CCS chain consist of three main stages: (i) Capturing of CO₂; (ii) transportation of CO₂ and (iii) Storing of CO₂ in a secure geological formation. Capturing the CO₂ essentially means to compress the gas into a sealed container. This usually also involves a separation process to extract the CO₂ from the flue gas (if capturing the CO₂ after combustion it would be mixed with air hence N₂, O₂ and water). Separation technologies include cryogenic process, solid or liquid absorption and selective membranes. Transport like any other gas can be done through compressed tanks or pipes. For storage, the carbon dioxide is injected into an underground geological formation (depleted oil or gas reservoirs are good candidates). Once injected, the carbon dioxide moves up through the storage site until it reaches an impermeable layer of rock (which cannot be penetrated by carbon dioxide) which traps it underground.

¹¹¹ Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, Ceramic sector, March 2015

¹¹² European Union Transaction Log (EUTL), extracted July 2017

¹¹³ Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, Ceramic sector, March 2015

Ideally this process is useful for large industrial processes, producing lots of CO₂ at high concentration. This saves costs (and energy) for separating the CO₂. Geographical proximity to the storage site is also a source of savings regarding CO₂ transport.

CCS can be done in three different methods:

- Pre-combustion capture; a process where the fuel (generally methane or coal) is reformed to hydrogen and CO₂, allowing the CO₂ to be stored and the hydrogen to be used as a fuel elsewhere. This process provides a near 100% concentration CO₂ stream.
- Post-combustion capture; is a process where the fuel is burned in a classical fashion, but the resulting fumes are captured. The CO₂ is then extracted from the stream and stored.
- Oxy-fuel combustion system separates oxygen and nitrogen from the air, and feeds only oxygen into the combustion chamber. The resulting gases from combustion are then trapped and stored. This technique has an advantage over the post-combustion capture, as the stream of gas created has a much higher concentration of CO₂, and the fuel burns more efficiently.

For ceramics production, the production of CO₂ is a result of the heat generation during the firing and drying processes. As such, classical combustion in the case of post-combustion capture would produce a gas stream of low CO₂ concentration. This is inefficient to capture. As such, a more effective process would be pre-combustion or oxy-fuel combustion. These technically could deliver 79% CO₂ emissions savings and are at relatively high TRL (5-8). However, the scale and economics of the technology are not favourable. The ceramic industry is mostly composed of SMEs, meaning their furnaces are small compared to other big industries, which makes the investment for a CCS technology difficult to justify. Perhaps as the technology develops there would be economies of scale, these are however not currently viable.

3.2.2.3 Decarbonisation with Novel techniques

Ceramic products (specifically on tiles) is increasingly deploying digitalisation techniques in interacting with clients which would result in cost savings and quality. At present, the techniques are centred on decorative purposes, but increasing interaction and product planning directly with customers will optimise the entire production process by producing the right number of products without unnecessary excess energy being wasted.

Vacuum drying technologies

Mitigation potential

Vacuum drying is used in many other sectors to remove water at low temperatures. This is of particular use for the food, chemicals and paper industries, which can't rely on high temperatures to prepare the product. For ceramics, vacuum could be combined with microwave or infrared (IR) for accelerated and more energy efficient drying.

Costs and TRL

Although the technology for vacuum drying has been available and commercially used for many years in other sectors, it has yet to become standard in the ceramics industry. This mainly comes down to cost as maintaining a vacuum sealed

environment is very costly. As such, so far, reusing waste heat from the firing kiln or IR/microwave technology has been more economical than vacuum drying. We estimate the TRL here to be at 6-7.

Application of technology

The technology is an optimisation of the drying process which consumes 26% of the total energy cost of manufacturing. This makes justifying the spend for a vacuum chamber difficult, as the firing process is a much bigger energy drain. Unfortunately, vacuum technology cannot be used to improve the firing kilns. The vacuum drying kilns would still require an IR or microwave installation and would not be able to use waste heat from the firing kiln.

Material recovery and Ceramic recycling

Mitigation potential

Material recovery such as sludge recycling, re-use from other industries, unmixed raw material feedback and broken ware feedback, allow for energy savings as they reduce the requirements for raw material preparation. Manufacturers have currently achieved new ceramic products with 70% recycled material.

Costs and TRL

Most of the manufacturing process of the recycled ceramic is the same as conventional ceramics. This implies that the cost to setup this technology is minimal. Although there are manufacturers using recycled material, these are still very few. As such the technology is estimated at a TRL of 6-7.

Application of technology

The difficulty with this technology is the setup of the collection for ceramic waste to be reused. The manufacturing process is largely the same, but ceramic users, along with building practices, would need to be guided by policy to encourage material recuperation and then transport to ceramic manufacturing plants for reprocessing.

Biomethane firing

Mitigation potential

As indicated in the conventional production process, the firing and drying processes consume 73% of the total energy requirement of the manufacturing of ceramics. These are mostly powered by gas. As such, one can use biomethane as a replacement source of heat. Doing so would bring the carbon emissions to a net 0, as the biomethane lifecycle would absorb the emitted CO₂ during production.

Costs and TRL

No capital costs would be incurred by switching to biomethane as the fuel. The technology is already used in other sectors (including the gas grid itself) and hence is ready for use by the ceramic industry.

Application of technology

The technology is ready to use. To deliver all the carbon savings, it requires for the system to be run on gas burners. More advanced drying and firing furnaces may have already made the switch to electric.

3.2.3 Glass

Glass product applications are in a state of evolution. Mainly used as methods of illumination in buildings and containers, new applications in high technology are appearing.

The novel decarbonisation options for glass are broadly categorised into 4 main groups:

1. **Process improvements** on our current manufacturing techniques, such as preheating batches, and better manufacturing control;
2. **Alternative fuels**, keeping the same general manufacturing processes but relying on fuels like biomass or electricity with a lower carbon footprint;
3. **Carbon capture storage systems** would allow the continuation of current manufacturing processes, but trap released gases from the process; and
4. **Circular economy techniques**, which investigate methods to recycle and reuse glass.

Table 3.3 and Table 3.4 presents the summary of decarbonisation options for the glass subsector.

Table 3.3 Technology readiness levels of selected mitigation options in the glass sub-sector

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency					
Fuel/Feedstock switch					Biomethane furnace Electric furnace
CCS and CCU	CCS glass and ceramics furnace				
Recycling and re-use				Circular economy glass reuse	
Material efficiency (downstream)					
Material substitution (downstream)					Glass Recycling

Table 3.4 Main characteristics of selected mitigation options glass sub-sector

Technology option	TRL	Max. emissions reductions ¹¹⁴	Electricity savings	Energy savings ¹¹⁵	Market entry	Reference Technology
CCS furnace	6 – 7	Up to 75%			2030+	Gas smelting

¹¹⁴ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

¹¹⁵ Energy savings show the reduction in energy consumption resulting from the technology change

Technology option	TRL	Max. emissions reductions ¹¹⁴	Electricity savings	Energy savings ¹¹⁵	Market entry	Reference Technology
electrification	6 – 7	Up to 75%	More efficient furnace heating	-56%	2020/2030	Gas smelting
Oxy-fuel combustion	6 – 8	Up to 46%	More efficient fuel burning	-20%	2025	Gas smelting
Batch preheating	8	Up to 33%	Heat reuse	-7%	2020	Gas furnace
Biomethane	10	Up to 75%			Present	Gas smelting
Glass recycling	9	Up to 41%	More efficient raw materials	-15%	present	Raw materials preparation and smelting

3.2.3.2 Conventional production process

The production of glass can be generally categorised into four main stages:

Raw materials preparation. The production process starts off with the preparation of raw material (generally sand) to produce the end-product. These processes include crushing, hammering, batching (measure and weighing), mixing and grinding, screening, atomisation, separation and filtering processes.

Smelting and refining. Melting, refining and homogenisation occurs simultaneously during the smelting process. Raw materials are heated up to 1,500°C in a furnace to produce molten glass. This step takes 75% of the energy costs of the entire process.

Forming. The forming process varies according to the type of products produced.

- Flat glass: The Pilkington production process is the most widely used process in flat glass forming.
- Moulded glass:
 - Blow processes
 - Press and blow processes
- Tubing glass:
 - Danner process
 - Vello process

Downstream processes. A variety of downstream processes follows the forming process. The following here are some of the common downstream processes:

- Surface treatment (hot end treatment, cold end treatment)
- Internal Fluorination Treatment
- Annealing (gradual cooling of glass)
- Cutting

The industry produces a total of 17,940 kT CO₂¹¹⁶. This is from an approximate intensity of 733 kg CO₂ / ton of glass produced, 77% of this energy is from fuel combustion during the manufacturing process, the remaining 23% is from electricity consumed.¹¹⁷

Incremental CO₂-reductions with BATs Decarbonisation BATs of the glass sub-sector is mainly centred around the smelting process. This can be optimised through improvements to the furnace construction, which could deliver 22% total emissions savings. Process control technologies also exist and will continue to improve as digitalisation and data prosper. Waste heat from the smelting process can be recovered for raw materials pre-heating and other waste heat recovery options (such as heat to power, or infrastructure heat). Oxy-fuel combustion, where oxygen and nitrogen are separated in air before combusting the oxygen, can also provide more efficient energy usage in the gas combustion process. These BATs technologies together are expected to deliver 30-35% energy savings to the EU glass industry.¹¹⁸

3.2.3.3 Decarbonisation through CCS

As described in the ceramics section, Carbon Capture Storage (CCS) chain consist of three main stages: (i) Capturing of CO₂; (ii) transportation of CO₂ and (iii) Storing of CO₂ in a secure geological formation.

As we previously described, CCS can be done in three different methods:

- Pre-combustion capture; a process where the fuel (generally methane or coal) is reformed to hydrogen and CO₂, allowing the CO₂ to be stored and the hydrogen to be used as a fuel elsewhere. This process provides a near 100% concentration CO₂ stream.
- Post-combustion capture; is a process where the fuel is burned in a classical fashion, but the resulting fumes are captured. The CO₂ is then extracted from the stream and stored.
- Oxy-fuel combustion system separates oxygen and nitrogen from the air, and feeds only oxygen into the combustion chamber. The resulting gases from combustion are then trapped and stored. This technique has an advantage over the post-combustion capture, as the stream of gas created is much higher concentration of CO₂, and the fuel burns more efficiently.

Within the glass industry, the oxy-fuel combustion system has already been used as a BAT to improve the efficiency of gas burning. Adding a capture system after this process would therefore be cost effective. Without capture, the technology reduces emissions by 17-20%. Already in operation the TRL is of 7, with investment under 50€ per ton of glass production capacity. This technology is therefore quite appropriate for the glass industry.

If a full capture system is implemented, the emissions can be reduced by a total of 75%. The capture and storage process are at a TRL of 5-8. Considering that glass

¹¹⁶ 2017 ETS values

¹¹⁷ Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, *Glass, 2015*

¹¹⁸ United Nations Industrial Development Organization (2011). Industrial Energy Efficiency for Sustainable Wealth Creation - Capturing environmental, economic and social dividends. p. 84.

industry is mainly composed of a few key large manufacturers, these have the means to invest in this new technology.

3.2.3.4 Decarbonisation with Novel techniques

Batch preheating

Mitigation potential

This technology means to capture and pass hot exhaust gases from back end of regenerators through either cullet or batch to recapture sensible heat plus re-absorb dust and SOx. It saves 7% of CO₂ from the conventional glass manufacturing process. It can therefore provide up to 1,256 kT of CO₂ emissions savings across the EU.

Costs and TRL

The technology is quite cheap as it is estimated to cost under 50 € per ton of capacity. It is already in use in some production plants and has a TRL of 8.

Application of technology

This process is a method of recovering waste heat from the smelting process. This provides savings yes, but as innovations such as electric heating and insulation of the smelter, there would be less waste heat available for batch preheating. That being said, it is a relatively easy technology to install as it can be set up complementarily to conventional manufacturing plants.

Glass recycling

Mitigation potential

Recycling is a well-established technology. Melting existing glass waste to make new items takes 15% less energy than making these from virgin sand.

Costs and TRL

The technology is ready and used already at TRL of 9. The collection for container glass is estimated above 50% for western EU countries. However Flat glass collection is still relatively low at about 10%. The costs from a manufacturer perspective are minimal. The real costs are rather social and policy wise to encourage mechanisms to ensure material efficiency.

Application of technology

Recycling glass not only reduces overall waste issues but also reduces the total energy usage of the industry. Glass is one of the few materials which when recycled will produce a like-for-like end product. This is a great advantage as in theory this could mean for a perfectly circular glass economy where no virgin material is required. This is apt, as of 2018, there is a global shortage on some of the sand raw materials.

Process electrification

Mitigation potential

Glass smelting furnaces are generally heated with oil or gas and can be replaced with all-electric heating systems. This is generally more used for smaller furnaces/

specialist glasses. All-electric heating is far more energy efficient as there are less exhaust and furnace losses. The process is directly 31% more efficient than conventional manufacturing methods. This can save 5,561 kT of CO₂ in the EU glass industry.

Costs and TRL

The process is estimated at medium costs between 100 – 500 € per ton of glass production capacity. The technology is already used, though not the norm and has a TRL of 5-8.

Application of technology

The process is more efficient and relies purely on electricity. As such, extra CO₂ emissions can be cut as the electricity grid becomes more renewable (up to 75% emissions cut). The process requires a lot of electricity which means the local grid would need to be reinforced to provide the power.

Biomethane furnace

Mitigation potential

The smelting process is mainly powered by gas and emits 75% of the process emissions of the manufacturing of glass. As such, one can use biomethane as a replacement source of heat. Doing so would bring the carbon emissions to a net 0, as the biomethane lifecycle would absorb the emitted CO₂ during production.

Costs and TRL

No capital costs would be incurred switching to biomethane as the fuel. The technology is already used in other sectors (including the gas grid itself) and hence is ready for use by ceramic industry.

Application of technology

The technology is ready to use. To deliver all the carbon savings, it requires for the system to be run on gas burners. More advanced drying and firing furnaces may have already made the switch to electric.

New fault detection technology

Mitigation potential

The process of casting glass requires the glass to be melted and then cooled at a steady temperature. As it cools, the crystallisation process occurs, ideally forming one perfect structure. Unfortunately faults in the glass can develop which won't meet the required glass quality. Approximately 15-20% of the glass from each cast must be recast due to faults. As smelting requires 75% of the energy in the glass manufacturing process, a process minimise the recasting could save up to 15% of the energy costs of a plant.

Costs and TRL

The technology isn't ready for development yet and is at a TRL of 2-3. It relies on spectroscopy whilst the glass is crystallising. As such, it would not require major refurbishment of the production line, which can keep the costs low after development.

Application of technology

The technology doesn't impede the current production process, it saves on energy costs and allows for a faster and higher quality production.

4 Pulp and Paper

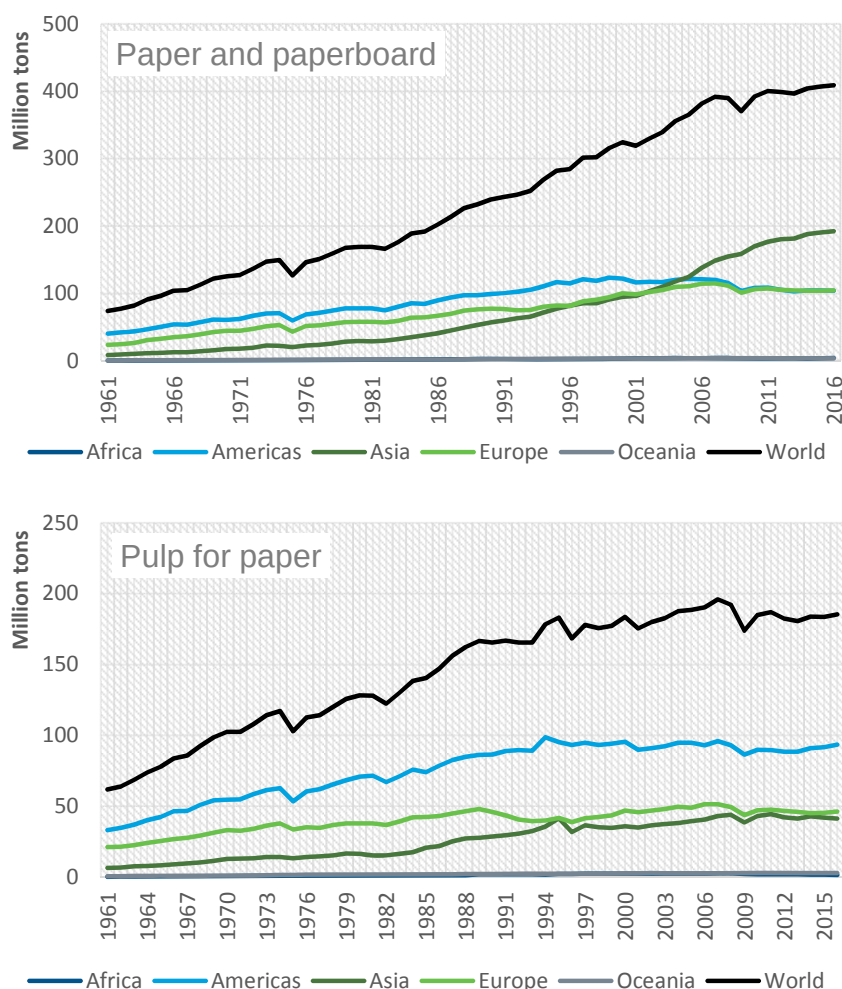
4.1 Core Products

The production of paper requires (wood-based) pulp as the main resource. Pulp is produced by either separating wood-fibres via mechanical wood grinding (mechanical pulp) or by separating fibres under high pressure using chemicals to cook the woodchips (chemical pulp). A third pulp production route processes fibres from recycled paper. The desired quality of the final paper or paperboard product determines the composition of the raw materials (e.g. fibrous materials, coatings, etc.) used as well as the further processing steps (e.g. bleaching, refining) and, consequently, its environmental impact. Drying the paper web is then an important energy-consuming process in paper mills.¹¹⁹ Typically, four different paper and paperboard grades can be distinguished: graphic papers, sanitary and household papers, packaging paper and paperboard, and special (other) paper and paperboard. In the following sections, key developments and trends in global paper and pulp markets are presented.

Figure 4.1 provides a comparison of global pulp for paper production (bottom) and global paper and paperboard production (top) by key regions from 1961 to 2016.

¹¹⁹ JRC 2015: Best available techniques (BAT), JRC Science and Policy Reports, Industrial emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

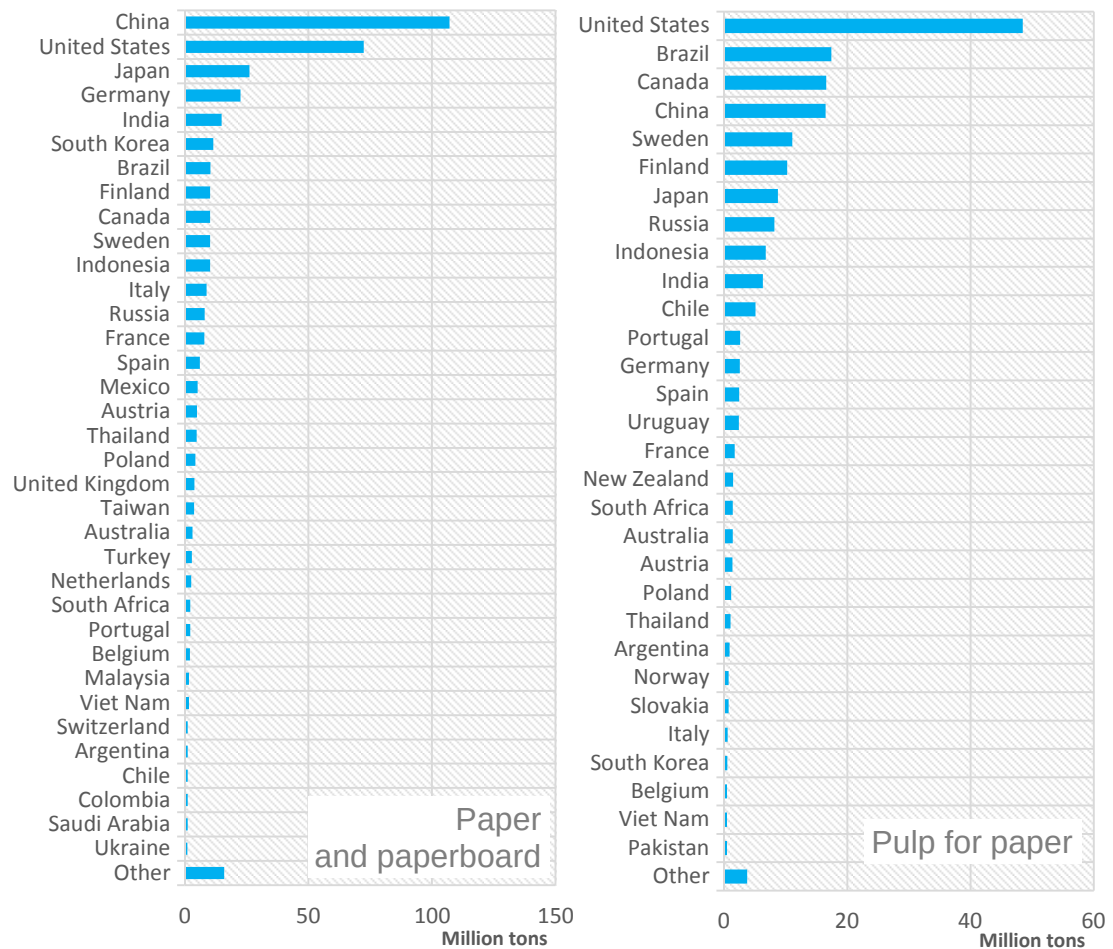
Figure 4.1 Global paper and paperboard (top) and pulp for paper (bottom) production by region 1961 - 2016¹²⁰



While global paper and paperboard production has been increasing steadily over the last decades (+2% per annum), Europe's share in production experienced an opposing trend, decreasing from 32% of global production in 1961 to 26% in 2016. The biggest contributor to global paper and paper production in 2016 is Asia (47%) followed by Europe (26%) and the Americas (25% of which around 20% were contributed by North America). Asian production is mainly dominated by China (Figure 4.2).

¹²⁰ FAOSTAT Forestry Protection and Trade (2018)

Figure 4.2 Paper and paperboard (left) and pulp for paper production (right) by country 2015¹²¹



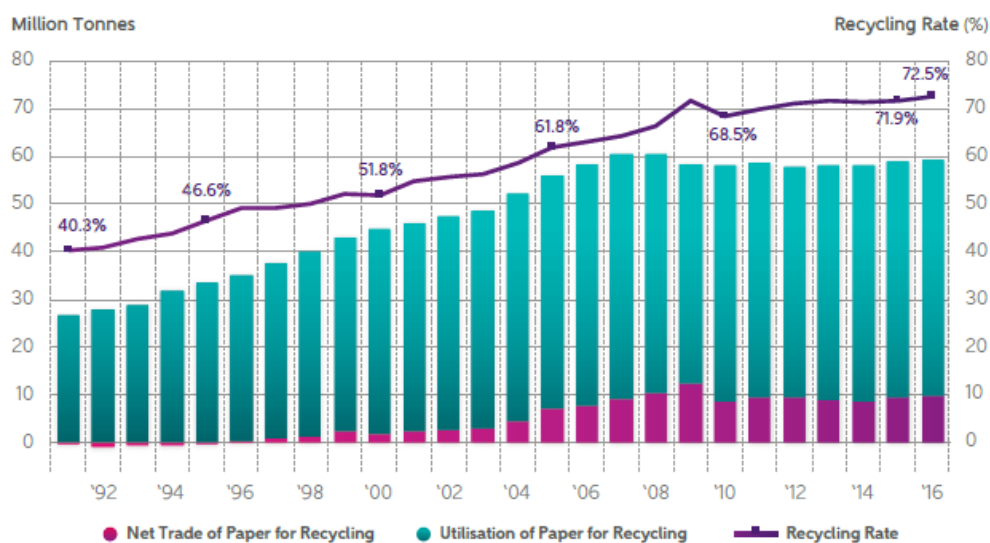
Over the last decades, the recycling rate of paper in Europe has increased substantially from an average of 40% in 1991 to 72.5% in 2016 (Figure 4.3). Recycled fibres are used for pulp production, which has a significant lower specific energy need compared to pulp production from virgin fibres.^{122,123}

¹²¹ FAOSTAT Forestry Protection and Trade (2018)

¹²² Fleiter, T. et al (2012): Energy Efficiency in the German pulp and paper industry – A model-assessment of saving potentials

¹²³ CEPI 2017: Key Statistics 2016. European Pulp and Paper Industry

Figure 4.3 Utilisation, Net Trade and Recycling Rate of Paper in Europe¹²⁴



4.2 Decarbonisation technologies

The decarbonisation options in the pulp and paper industry are discussed by distinguishing both best available technologies (BATs) and innovations/ break-through technologies. Figure 4.4 presents an overview of selected mitigation opportunities across the paper production value chain.

The TRL-levels of the investigated mitigation options are presented in Table 4.1.

¹²⁴ CEPI (2017) : Key Statistics 2016. European Pulp and Paper Industry

Table 4.1 Technology readiness levels (TRL) of selected mitigation options in the pulp and paper industry

Clusters of mitigation options	TRL5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement / energy efficiency	Deep eutectic solvents	New drying techniques	Enzymatic pre-treatment	Black liquor gasification	
	Waterless paper production			new raw materials (e.g. grass)	
Fuel switch					Electricity for process heat
CCS and CCU					
Recycling and re-use	Urban refinery		Improved recycling/sorting technologies		
Material efficiency (downstream)		Lightweight papermaking			
Material substitution (downstream)		New materials replacing e.g. plastics			

Table 4.2 Main characteristics of selected mitigation options for the pulp and paper industry¹²⁵

Technology option	TRL	Max. emissions reductions ¹²⁶	Energy savings ¹²⁷	Market entry	Reference technology
Black liquor gasification	8 - 9	Up to 10% ¹²⁸	Up to 15%	<2020	Conventional chemical pulping process
New drying techniques	5 - 7	Up to 20%	Up to 10%	2020	Conventional paper mill
Enzymatic pre-treatment	6 - 8	n.a.	Up to 25%	<2025	Conventional mechanical pulping process
Deep eutectic solvent pulping	3	Process dependent	Up to 40% ¹²⁹	2030-2035	Conventional mechanical, chemical pulping process
Flash condensing	3 - 4	Up to 50%	Up to 20%	2025-2030	Conventional chemical

¹²⁵ WSP Parsons Brinckerhoff (WSP) und DNV-GL (2015), Fleiter et al. (2013), Fleiter et al. (2012), CEPI 2013, CEPI (2017b), IF (2017), own estimations, expert interviews,

¹²⁶ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

¹²⁷ Energy savings show the reduction in energy consumption resulting from the technology change

¹²⁸ Max emissions are here lower than the energy savings as the site reuses waste heat from the process.

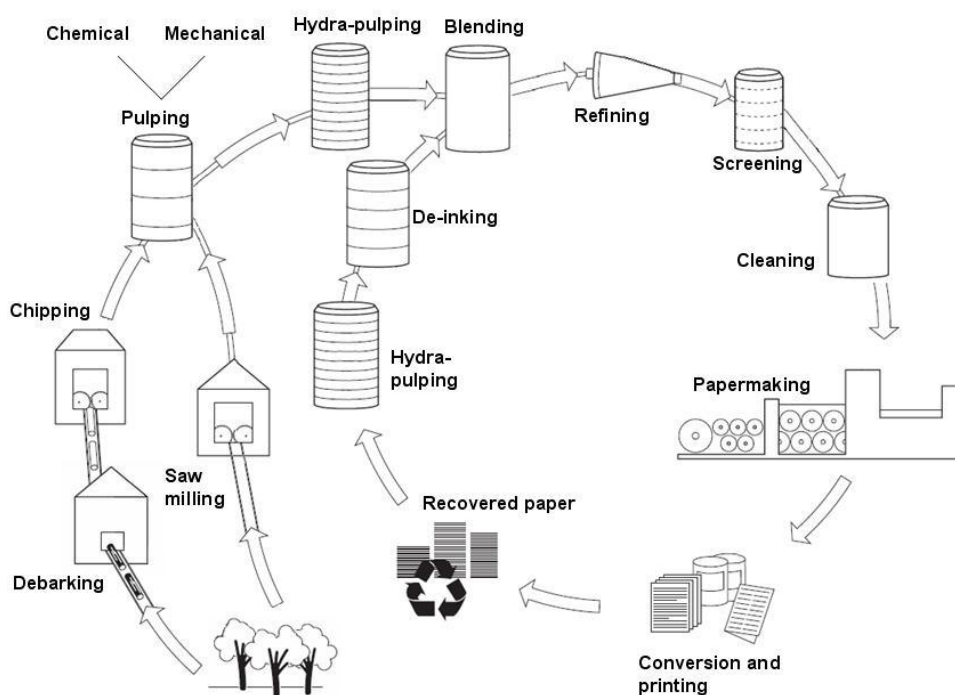
¹²⁹ Provides (2017): Carbon reduction in the paper industry by DES. Finance for Innovation: Towards the ETS Innovation Fund. 23 March 2017, Brussels.

Technology option	TRL	Max. emissions reductions ¹²⁶	Energy savings ¹²⁷	Market entry	Reference technology
					pulping process

4.2.1.2 Current production process

The production of **pulp** and its further processing into **paper web** are the most energy-intensive process steps in the paper production process. Pulp is produced from wood (chemical or mechanical pulp), while recovered pulp fibres are obtained from recycled paper. The pulp is processed into a paper web in the paper mill. Additional non-fibre resources such as fillers or additives are used in smaller quantities. The three different pulp production lines differ in energy intensity and product properties. The core process of papermaking differs according to paper type (raw materials used, such as fibrous materials, coatings and other processing steps, such as bleaching, finishing; Table 4.3) and between integrated and non-integrated plants, with minor differences compared to the differences in pulp production plants.¹³⁰

Figure 4.4 Process steps for integrated paper and paperboard production¹³¹



In the production of **mechanical pulp**, wood is ground and refined to obtain a fibrous pulp. A typical by-product are large quantities of waste heat. **Chemical pulp** is produced using chemicals (sulphite or sulphate), with which the lignin content is separated from the wood fibres in a cooking process. The lignin (approx. 50% of the initial wood content) is then burned to produce the high steam quantities required for this process. A third process is the production of **pulp from recycled paper**. Many

¹³⁰ Fleiter, T. et al (2012): Energy Efficiency in the German pulp and paper industry – A model-assessment of saving potentials

¹³¹ JRC (2015)

paper mills are integrated, and it is often not possible to draw clear boundaries between the processes.

Table 4.3 Main grades of paper and paperboard¹³² (based on JRC 2015)

Grades of paper and paperboard	
Graphic papers	Newsprint: used for printing newspapers. Produced mainly from mechanical pulp and/or paper for recycling. Mill with paper machine: ~ 300 000 tonnes/year. Uncoated mechanical: for printing or other graphic purposes (less than 90 % chemical pulp fibres). Large-scale integrated mills: ~250 000 tonnes/ year. Uncoated wood-free: for printing or other graphic purposes, e.g. office papers (at least 90 % chemical pulp fibres, free of wood-particles and lignin). Paper machine: ~150 000 tonnes/year. Coated papers: all paper suitable for printing or other graphic purposes that is coated on one or both sides.
Sanitary and Household	Tissue and other hygienic papers: Parent reel stock made from virgin pulp, recovered fibre or a mixture. Machine capacity: ~30 000 – 60 000 tonnes/year.
Packaging	Case materials: mainly used in manufacture of corrugated board. Made from a mix of virgin and recovered fibres. Carton board: good folding properties, stiffness and scoring ability. Made from virgin and/or recovered fibres. Paper machine: ~ 33 000 tonnes/year¹³³. Wrappings Other papers mainly for packaging purposes: produced mainly from recovered fibres.
Special (Other)	Other paper and board for industrial and special purposes: e.g. cigarette papers, filter papers, thermal paper, self-copy paper, sticking labels as well as gypsum liners and special papers for waxing, insulating, roofing, asphaltting, and other specific applications or treatments.

4.2.1.3 Incremental CO₂-reductions with BATs

Today's mitigation efforts concentrate on two main approaches:

- improving energy efficiency, and
- switching to low-carbon/renewable fuels and renewable electricity.

The European Paper industry has greatly improved its energy efficiency over the last few decades through waste heat recovery and improved drying techniques. As such, the remaining energy efficiency potential through best available technologies (BAT) are limited. In addition, fuel switching from fossil fuels to renewable sources like biomass is already occurring. As illustrated in Figure 4.5, in 2014, approximately 47% of fuel (excluding electricity) consumed in pulp and paper production was from renewable sources. However, the competition for biomass with other sectors represents a challenge.

Improving energy efficiency

For paper production, efforts concentrate on the efficiency of paper drying - the process step that consumes the largest share of steam. Commercially available

¹³² JRC (2015); Friedrichsen and Herbst (2016)

¹³³ Mills in Finland and Sweden are relatively big: 100 000 – 150 000 tonnes/year.

technologies, like the **steam box** or the **shoe press**, aim to improve mechanical dewatering to reduce the need for thermal drying.¹³⁴ Although these techniques are already widespread, there is still potential for greater diffusion.

New refining concepts like for example compression refining that claim huge efficiency gains of up to 20 or 30 % have been entering the market in recent years^{135,136}.

To produce mechanical pulp, energy-efficiency improvements concentrate on the **grinding and refining** of the wood, where several innovative concepts were developed in the last decade¹³⁷.

Although the **recovery of waste heat** is already widespread, significant potential is still available through the use of waste heat from refiners and grinders, the dryer section in the paper machine, and effluent water. Furthermore, low temperature heat, as well as improved optimisation of the steam system offers potential.

Alternative fuel use (and electricity)

Historic development shows that the European pulp and paper industry have increased the use of alternative fuels. For example, **biomass** consumption has increased from 22% in 1990 to about 36% in 2014, this has been accompanied by decrease in fuel oil. Biomass is mainly obtained from production residues (e.g. the lignin in the chemical pulping route).

Electrification of steam generation

Using renewable electricity rather than fossil fuels to generate process heat can cut all direct CO₂ emissions. However, current electricity prices prevent a large-scale use of electricity for steam generation.

Demand side flexibility

Increasing shares of volatile renewable energy sources in the electricity grid system will increase the need for flexible technologies to match demand and supply more closely. The paper industry can even with today's technologies play a more active role. **Demand response** potentials are among others available for the production of mechanical pulp (high electricity use for wood grinding) depending on the size of the pulp storage. By exploiting its on-site combined heat and power plants, the paper industry can engage in the energy market and adapt its energy procurement to achieve low prices, through surpluses from intermittent renewable energy sources.

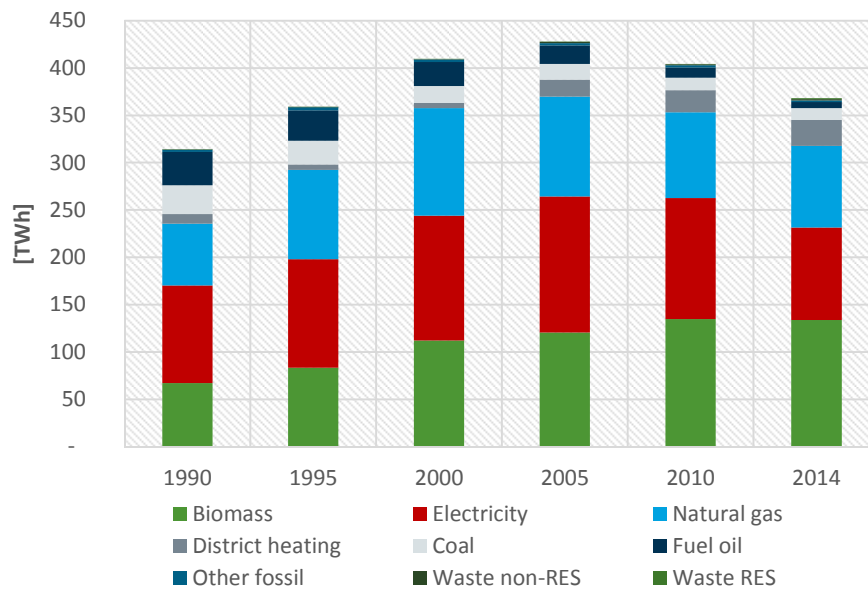
¹³⁴ Luiten, Esther; Blok, Kornelis (2004): Stimulating R&D of industrial; energy-efficient technology. Policy lessons – impulse technology

¹³⁵ Dekker, J.C. (2008): Kompressionsmahlung: Die Entwicklung einer neuen Mahltechnologie zur Energieeinsparung bei der Papierherstellung: PTS Paper Symposium 2008

¹³⁶ Blum, O.; Maur, B.; Öller, H.-J. (2007): Revision of Best Available Technique Reference Document for the Pulp & Paper Industry: Use of Energy Saving Techniques, Papiertechnische Stiftung (PTS) (ed.), München.

¹³⁷ Franzen, R. (2006): Recent developments in mechanical pulping. In: ipw - The magazine for the international pulp & paper industry, 9/2006, pp. 52-56.

Figure 4.5 EU 28 final energy demand in pulp, paper and printing by energy carrier¹³⁸



4.2.1.4 Decarbonisation with Novel techniques

Compared to other energy-intensive industries, the pulp and paper has several advantages regarding decarbonisation. First, the industry has direct access to biomass resources. Second, the paper industry only generates energy-related but no process-related emissions which are much more difficult to reduce. Third, the demand for steam in the paper industry is quite flexible in terms of the energy carrier used for its production (in contrast to furnaces in the high-temperature range, e.g. in the steel industry).

However, many challenges still need to be overcome and research on sustainable paper production technologies is ongoing. Selected breakthrough technologies are described below.

Black liquor gasification

Black liquor gasification (BLG) is a technique used in pulp mills to generate surplus electricity or bio fuels. In the black liquor gasification process, concentrated black liquor is converted into inorganic compounds (mainly sodium and sulphur) suitable for the recovery of cooking chemicals and combustible fuel gas comprising primarily hydrogen and carbon monoxide (syngas). After separation, the clean gas can be fired in a gas turbine for power generation while the hot flue gases can be used to generate steam in a waste-heat boiler. The resulting high-pressure steam gases can generate additional power in a steam turbine. BLG is often discussed in the context of the future paper factory becoming a bio refinery.¹³⁹

Mitigation potential

¹³⁸ Eurostat

¹³⁹ JRC 2015

BLG has an energy saving potential of maximum 87% of electricity demand, (Fleiter et al. 2012) and can result in an estimated CO₂-emission reduction of approx. 10% compared to the reference technology (i.e., conventional chemical pulping process).

Costs and TRL

Black liquor gasification is a technology with a long R&D history and a high TRL of 8-9. However, the turbine and gasifier technology still need to be further developed due to mill fluctuations and low heating value fuels.¹⁴⁰ Although this technology is already well developed, it is currently not widely used. The initial differential investment¹⁴¹ of such an installation is estimated between 300 and 500 € per tonne annual capacity.

New drying techniques

Drying the paper web is the major energy-consuming process in a paper mill. Literature discusses various new drying techniques that might result in energy efficiency improvements and CO₂-emission reductions. The actual energy saving potential is currently not clearly known, as is the time of earliest commercial application. Examples for such innovative drying techniques are steam/air impingement drying, condensing belt drying and impulse drying¹⁴². The progress of these technologies in recent years is uncertain.¹⁴³

Mitigation potential

Fleiter et al. 2012 estimate that new drying technologies might achieve emission reductions of up to 20% compared to a conventional paper mill, and reduce fuel demand (biomass, natural gas) by approx. 12%.

Costs and TRL

Compared to other technologies (e.g. BLG) the required additional investments in these technologies are relatively low. However, there is also a large uncertainty and they depend strongly on the specific technical concept. The potential TRLs might range from low to relatively high depending on the specific concept. Potential barriers for market introduction are low achievable paper quality, costs and slow diffusion through the paper machine stock due to long average lifetimes (20-40 years). (Fleiter et al. 2012, interviews)

Flash condensing with steam

High-consistency largely dry fibres, fillers, and chemicals are blasted into a forming zone with agitated steam and are condensed into a web using only very small amounts of water (nearly waterless). In addition, very little extra heating is required for drying, due to the low water content. Steam forming can be most easily applied to chemical pulp but would also work for recovered fibres. Currently steam forming

¹⁴⁰ JRC 2015

¹⁴¹ compared to the reference technology: conventional chemical pulping process

¹⁴² Fleiter, Tobias; Fehrenbach, Daniel; Worrell, Ernst; Eichhammer, Wolfgang (2012): Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials.

¹⁴³ Laurijssen, J.; Gram, F. J. de; Worrell, E.; Faaij, A. (2010): Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry.

is at least 10 years away from becoming commercially available and needs further R&D.¹⁴⁴

Mitigation potential

Flash condensing with steam is expected to achieve a maximum CO₂ emissions reduction of 50% and energy savings of at least 50% in the drying process, compared to conventional pulping.

Costs and TRL

At TRL 3-4, market entry is expected between 2025 and 2030 as the fluidising of fibres in water vapour needs further research as well as the process to achieve inter-fibre bond formation during drying.¹⁴⁵

Enzymatic pre-treatment

Pre-treating wood chips using enzymes reduces the mechanical energy needed for wood processing. A variety of processes and enzymes have been discussed since the 1980s, but no single dominant process design has evolved so far. New approaches combine the use of enzymes with low-intensity refining to improve the penetration of the enzymes into the wood.

Mitigation potential

Enzymatic pre-treatment has an electricity saving potential of 10 to 40%, depending on the type of enzymes and the process design compared to the reference technology (i.e., conventional mechanical pulping process).

Costs and TRL

The initial differential investment¹⁴⁶ of such an installation is estimated around 400 € per tonne annual capacity. With a TRL of 6-8, further research is needed to push this technology to market.¹⁴⁷

Deep eutectic solvent pulping

Deep Eutectic Solvents (DESSs) can be used in a new pulping technology for wood and aggro-based lignocellulose raw materials as they are a new class of natural solvents that have the ability to dissolve and fractionate lignin, hemicellulose and cellulose at low temperature and atmospheric pressure, for further processing into high added value materials and chemicals.¹⁴⁸ DESSs can also be used to recover pure cellulose from papermaking residues and to dissolve ink and contaminants in recovered paper.

Mitigation potential

Replacing chemical and mechanical pulping processes, primary energy demand can be reduced by around 40% compared to conventional pulping processes. Emission reductions depend on the type of process replaced (chemical pulping or mechanical pulping). However, the true savings of this technology could be significantly higher

¹⁴⁴ CEPI 2013: The Two Team Project. Brussels.

¹⁴⁵ CEPI 2013: The Two Team Project. Brussels.

¹⁴⁶ compared to the reference technology: conventional mechanical pulping process

¹⁴⁷ Fleiter, Tobias; Fehrenbach, Daniel; Worrell, Ernst; Eichhammer, Wolfgang (2012): Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials. CEPI 2013

¹⁴⁸ Provides 2018: Deep Eutectic Solvents for Sustainable Paper Production. www.providespaper.eu

considering the potential spill over effects to other industries by providing building blocks for bio chemicals, materials or fuels.¹⁴⁹

Costs and TRL

Currently at TRL 2-3, DESs are proven at lab-scale but have not yet been tested in pilot, demo or industrial projects. Due to its many different application possibilities, the development of this separation technology is ongoing. It is aimed to develop a DES pulping pilot by 2020 with the goal of reaching industrial scale in 2030 (latest 2035) if the necessary conditions are met (e.g. funding programmes and/or regulatory frameworks). However, capacity of future installations will be significantly lower than in ordinary pulping plants. The technology aims to achieve equal investment costs compared to a conventional chemical pulping plant. The sale of resulting by-products could be an additional income source for a pulp plant using DES.¹⁵⁰

Light-weight paper making

The lightweight papermaking aims at producing light and resistant high-performance materials and products using nanocellulose; e.g. cellulose nanofibrils (CNF) or cellulose nanocrystals (CNC). CNF can be produced by the disintegration of wood fibres using mechanical shears and/or pressure before and/or after a chemical or enzymatic treatment. CNC are produced by acidic hydrolysis of cellulose fibrils giving high transparency. For the future, there are a variety of potential applications for this technology, e.g. low-end large-scale commodity applications in the pulp and paper sector (strength additives and barrier/coating applications) but also in other sectors like for example the electronics and ICT, automotive, packaging and the building industry.¹⁵¹

Mitigation potential

A general CO₂ saving cannot be estimated as this depends on the product concerned. However, the technology aims to reduce the amount of material produced by 30% per square metre.¹⁵²

Costs and TRL

Depending on the type of use, the TRLs vary for the technology. The Stora Enso has already successfully launched a commercial paperboard packaging plant using micro fibrillated cellulose¹⁵³. In Sweden, pilot and commercial production facilities for CNF are already in place.¹⁵⁴ CNCs are produced at an industrial scale for pre-

¹⁴⁹ Provides 2017: Finance for Innovation: Towards the ETS Innovation Fund. Carbon reduction in the paper industry by Deep Eutectic Solvents. Presentation Provides. Brussels.

¹⁵⁰ interviews

¹⁵¹ RISE n.a: Roadmap 2015 to 2025: Materials from nanocellulose.

¹⁵² CEPI 2013: The Two Team Project. Brussels.

¹⁵³ Stora Enso 2017: A future for MFC. <http://www.storaenso.com/newsandmedia/a-future-for-mfc>

¹⁵⁴ Z. Karim et al. 2016. *High-flux affinity membranes based on cellulose nanocomposites for removal of heavy metal ions from industrial effluents*

commercial development in Canada and the US. However, Research is ongoing into new raw materials, into modification of existing materials, etc.¹⁵⁵

New raw materials

A rather new concept is the production of paper from new raw materials, e.g. the development of straw paper, grass paper and other agricultural residues. When producing paper from e.g. grass, less energy, chemicals and water is used due to the lower lignin concentration in the raw material. Further, it reduces the pressure on wood resources¹⁵⁶.

Improved recycling rates

The average European recycling rate is about 72.3%, however, national recycling rates can differ strongly indicating that there is still room for improvement. Recycled fibre quality can be improved by improving the collection, sorting (e.g. by filler content, brightness, fibre length) and eco-design for recycling. This will improve the efficiency of the treatment and refining of fibres.¹⁵⁷ Urban refinery

The concept of the "Urban refinery" is motivated by the imperfect paper recycling chain of today. It is both very fragmented and wasteful, with about 20% of the material input to produce recovered pulp, not used and considered waste. This rejected waste material consists of all kinds of materials including chemical additives, minerals, printing ink and contains only a small share of fibres. The urban refinery aims to improve this situation by processing waste paper using all by-products, not just fibres. Further, it aims to provide better-defined and high-quality fibres, which potentially can reduce the technical efforts for pulp preparation in paper mills substantially. This leads to a better utilization of the total amount of recovered paper/recyclable waste.

As such, the vision of the urban refinery reflects the circular economy (no waste), local symbiosis with the urban area and industrial symbiosis by supplying raw materials e.g. to the chemical industry. However, with a regional focus, production capacities will likely be much lower than in today's pulp plants.¹⁵⁸

Supercritical CO₂

Supercritical CO₂ has been proposed in the 2013 CEPI "Two team project" to dry pulp and paper without heat and steam using high pressure and temperature. Supercritical CO₂ is already used in other sectors like the food or textile industry. In the paper industry, supercritical CO₂ has been tested on a lab-scale, but no further efforts are currently known to develop this technology to a higher TRL. Under these preconditions it is currently unlikely that supercritical CO₂ will become commercially available for the paper industry.¹⁵⁹

¹⁵⁵ RISE n.a: Roadmap 2015 to 2025: Materials from nanocellulose.

https://www.ri.se/sites/default/files/files/docs/roadmap_materials_from_nanocellulose.pdf CEPI 2013: The Two Team Project. Brussels.

¹⁵⁶ www.creapaper.de

¹⁵⁷ CEPI Press release, 24/10/2018

¹⁵⁸ Miletzky, Frank (2017): Circular Economy by new Recycling of paper. Finance for Innovation Workshop Brussels, March 23, 2017. PTS. Brussels.

¹⁵⁹ CEPI 2013: The Two Team Project. Brussels. interviews

Waterless paper production

Up to now, waterless paper production has only been examined on a laboratory scale. The main aim of this innovation is to use biopolymers instead of water. Currently, this technology is a purely theoretical concept and further research activities do not seem to be taking place in this area due to paper quality issues (e.g. the required degree of whiteness cannot be achieved).¹⁶⁰

¹⁶⁰ interviews

5 Non-ferrous metals

5.1 Core Products

As 51% of EU ETS CO₂ emissions for non-ferrous metals are attributable to Aluminium production, it is the biggest contributor to the non-ferrous metals sector. Copper production is the next highest contributor of CO₂ emissions, but it is expected to increase in usage over the coming years, due to the importance of its high electrical conductivity properties. As such, this section focuses on aluminium and copper production.

5.1.1 Aluminium

Alumina (also known as aluminium oxide) is produced from bauxite ore which is the primary source of aluminium. Alumina is extracted from bauxite ore through the Bayer¹⁶¹ chemical process, which takes the form of white powder. Alumina is the main raw material for primary production of aluminium through the smelting process. In addition to the production of aluminium, alumina is also used as filler for plastic, production of automotive paint. Large quantities of alumina are also used in refineries for the conversion of dangerous hydrogen sulphide into elemental sulphur.¹⁶²

Primary Aluminium is produced through smelting (or reduction) plants, where pure aluminium is extracted from alumina through the Hall-Héroult electrolysis process¹⁶³, whereby the reduction of alumina into liquid aluminium is operated at >950 °C under a high intensity electrical current. For this reason, many aluminium production plants are located near to dedicated, low cost, hydropower supplies to avoid energy losses (examples are Fort William in Scotland, Karmoy in Norway, Krasnoyarsk in Russia) – the layout and shape of the ‘busbars’ that carry the current is an important factor in reducing energy losses. The number of Aluminium smelting plants in the EU has decreased from 26 plants in 2002 to 16 plants in 2016.¹⁶⁴

Secondary Aluminium is produced from re-melting aluminium material recovered from waste streams and recycling process. The collected material is fed into a melting furnace operating at temperatures ranging from 700 – 760 °C.

Aluminium’s intrinsic properties have contributed to its growing popularity and uses¹⁶⁵. These include:

- **Lightness:** Its density is 2.7 g/cm³, one-third that of steel. In vehicles, aluminium reduces unnecessary weight and therefore fuel consumption.
- **Strength:** Aluminium’s strength can be adapted to the application, by modifying the composition of its alloys. Certain alloys are as strong as steel.

¹⁶¹ The Bayer process is the primary chemical process of extracting alumina from bauxite ore, which was developed in 1887 and still used in nearly all of the world’s alumina supply

¹⁶² The Aluminium Association

¹⁶³ The Hall-Héroult process involves dissolving alumina into a molten cryolite bath and passing current through the mixture causing the oxygen atoms to separate from the alumina and resulting in aluminium.

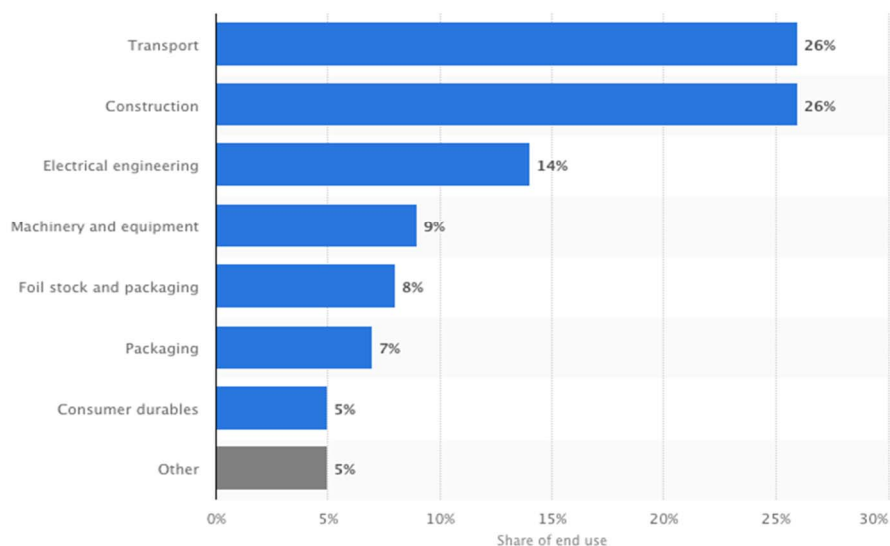
¹⁶⁴ European Aluminium Association, 2018

¹⁶⁵ “What are the properties of Aluminium?” - <http://www.constellium.com/aluminium-company/aluminium-properties-and-uses>

- **Corrosion-resistance:** Naturally generating a protective oxide coating, aluminium is particularly useful for protection and conservation.
- **Conductivity:** Twice as good a conductor of heat and electricity as copper (based on weight), aluminium is now playing a major role in power transmission lines.
- **Ductility:** Its low density and melting point allow aluminium products to be formed up until the last stages of a product design.
- **Reflective:** As a reflector of heat and light, aluminium is suitable for such applications as solar technology and rescue blankets.
- **Impermeable and odourless:** Releasing no taste or toxins, aluminium is ideal for food and pharmaceutical packaging.
- **Recyclability:** Aluminium is 100% and infinitely recyclable with no deterioration in quality.

Unsurprisingly, transport, construction, electrical equipment, packaging and consumer durables all feature amongst its existing (and predicted future) applications:

Figure 5.1 Global demand for semi-finished aluminium products in 2016¹⁶⁶



5.1.2 Copper

Blister is an intermediate copper product containing 98.5 – 99.5% copper. Copper ore and concentrates go through a roasting process prior to being fed into a smelter resulting in a copper matte, containing 50 – 70% copper. The molten matte then follows a conversion process to produce blister copper.

Copper anode is a product of the copper refining process containing around 99% pure copper. Blister copper is fire refined (anode furnace) through traditional process route, and progressively re-melted and cast into anodes for electro-refining.

Copper Cathode is a result of the electro-refining process and contains 99.99% pure copper. An electrolytic cell is used and consists of a cast copper anode and a cathode, made of pure copper to act as a starter sheet, placed in an electrolyte that

¹⁶⁶ Statista, 2018

contains copper sulphate and sulphuric acid. High current density is applied through the solution and pure copper is deposited on the cathode.

Copper is an excellent electricity conductor and most of its end-uses relate to these applications, such as motors, transformers, cables.

5.2 Decarbonisation technologies

To provide visibility on decarbonisation options, the report will first study and elaborate on conventional manufacturing methods. This will provide a comparison baseline from which to evaluate other decarbonisation technologies. This baseline is compared with: (i) current Best Available Technologies (BAT); Carbon Capture and Storage (CCS) options; and (iii) novel decarbonisation technologies.

5.2.1 Aluminium

Aluminium is a major CO₂ emitter during its production, but has applications, notably with improved electronics, low density and resistance to oxidation, which make it a material capable of delivering savings across many industries. It is also highly recyclable, bringing new aspects of circular economy thinking.

The decarbonisation options for Aluminium are broadly categorised into three main categories:

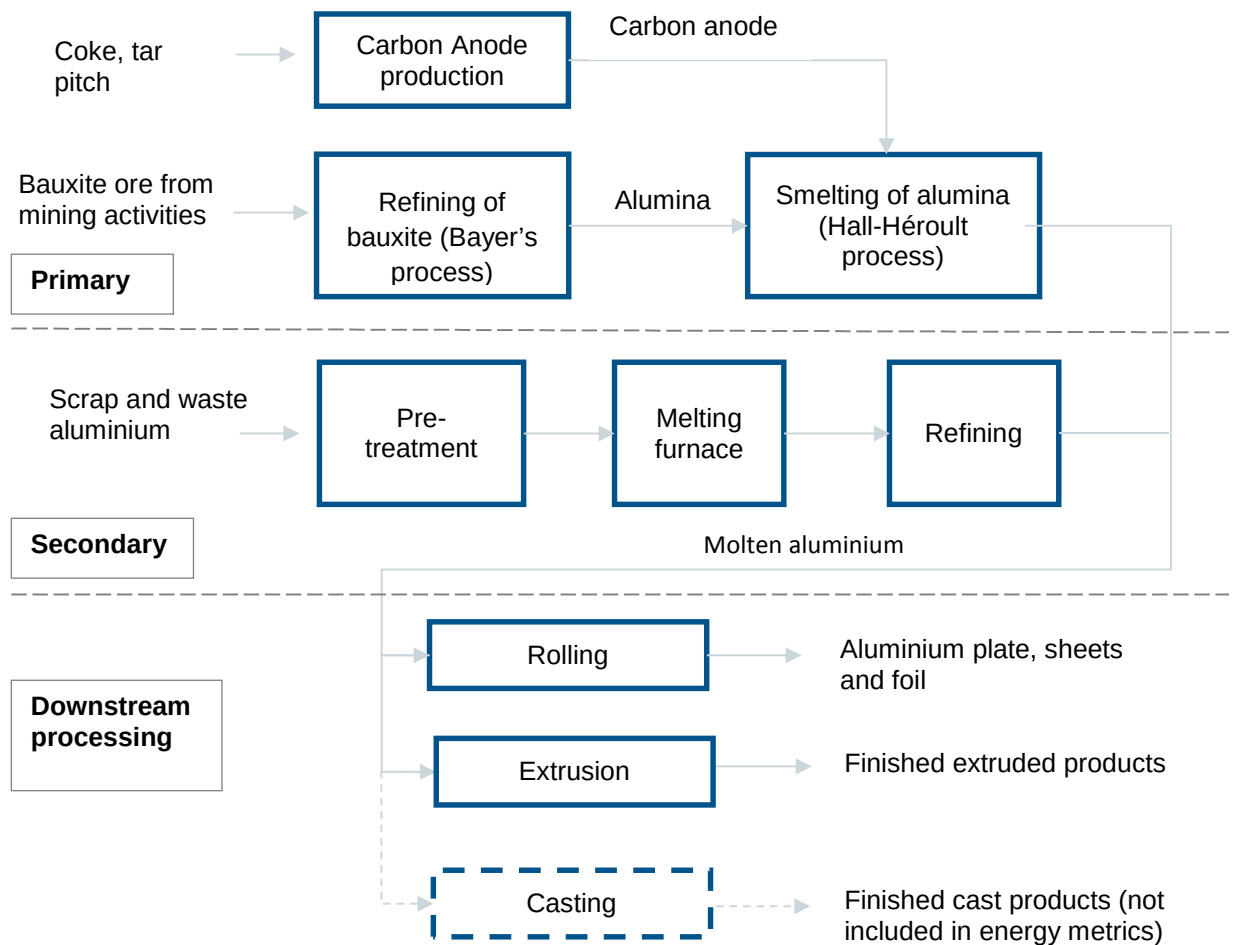
1. **Process improvements** on our current manufacturing techniques;
2. **New production techniques** using innovative technologies to move away from current production, more efficient and emitting less CO₂;
3. **Feedstock innovations**, using improved techniques to treat alumina, or sourcing aluminium from new materials with a smaller CO₂ footprint.

5.2.1.1 Conventional production methods

Overview

Figure 5.2 provides an overview of primary and secondary aluminium processes.

Figure 5.2 Overview of primary and secondary aluminium production

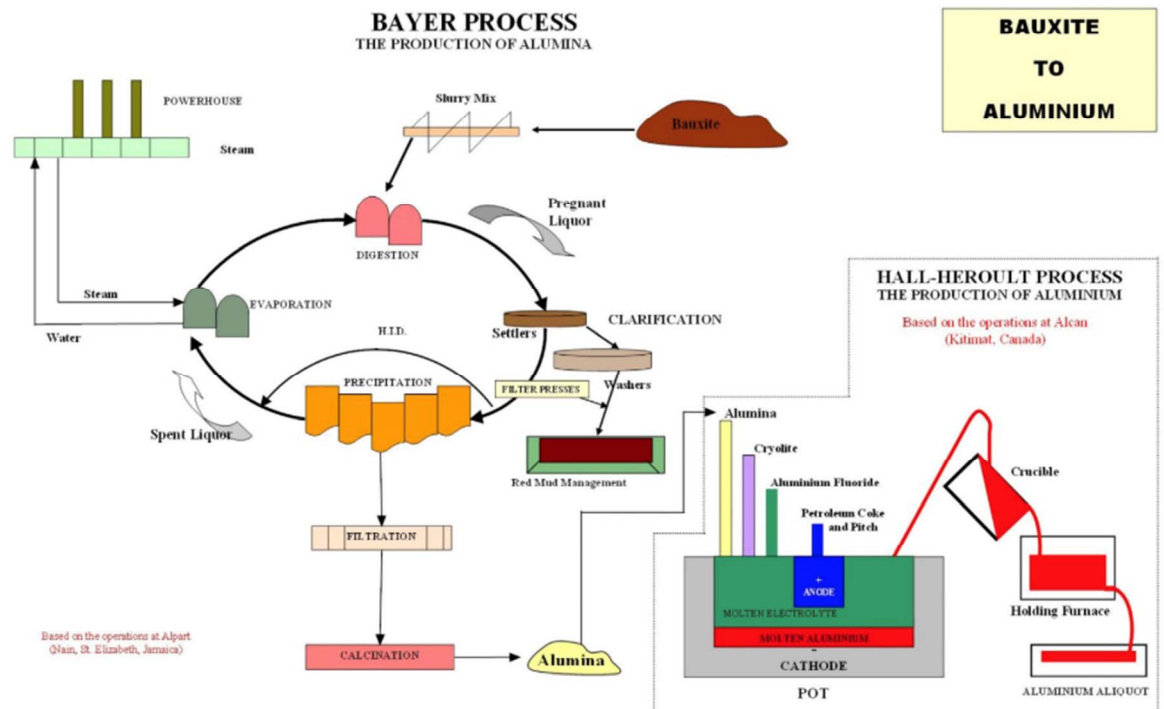


The following sections provide more detail on the key steps in primary and secondary aluminium making.

Primary Aluminium smelting

Conventional aluminium smelting from ore is a multi-stage, energy-intensive process. It is useful to have an appreciation of this entire process because it helps keep things in perspective. Also, some BAT or innovative technologies can impact on one or more stages, or even eliminate some stages.

Figure 5.3 Schematic of the Bayer process for aluminium production¹⁶⁷



Bauxite Production

'Bauxite' refers to ores that contain a high (> 35%) concentration of aluminium hydroxide minerals. The three main types are: gibbsite, boehmite and diaspor.

Bauxite mining begins with mechanical removal of the overburden layer covering the bauxite, which ranges from 2-20 meters in depth. Bauxite deposits tend to be soft and earthy; high-energy operations like drilling and blasting are not required. In addition, bauxite mines are often open-pit, eliminating the need for ventilation and de-watering processes.

Loading and hauling is the most energy-intensive process. Bauxite requires minimal processing before moving to an alumina production plant. It may be crushed, ground, and beneficiated, with beneficiation used mainly to remove clay. This can be achieved by washing, wet screening, cycloning, or sorting. The estimated primary energy demand for producing bauxite is about 278 kWh/ton (1 GJ/ton)

Alumina Production

The Bayer Process, which refines bauxite into alumina, is the main alumina production process used throughout the world. The process is estimated to require about 4028 kWh/ton (14.5 GJ/ton) of alumina. As a rule of thumb:

- about 2 t bauxite produce 1 t alumina,
- about 2 t alumina are required to produce 1 t of aluminium.

Digestion

¹⁶⁷ http://www.jbi.org.jm/pages/bayer_process

Mined bauxite is first washed and crushed to increase the surface area available for reaction. Some bauxite goes through desilication to remove impurities. The bauxite is then dissolved in a series of high-pressure digesters with the addition of a caustic soda solution.

Clarification and Precipitation

Clarification separates solid bauxite residue ('red mud') from the sodium aluminate. The sediment sinks to the bottom of settling tanks and is removed. The sodium aluminate solution is filtered further. Cooling the sodium aluminate solution and adding mineral crystals leads to precipitation of hydrated alumina crystals ($\text{Al}(\text{OH})_3$). Cyclones or gravity classification tanks separate coarse crystals out for calcination.

Calcination

Coarse crystals are baked in calciners at high temperature (900-1300 °C) to remove water of hydration and produce metallurgical-grade-purity alumina (Al_2O_3).

Alumina calciners use a range of technologies, including gas suspension calciners (GSC), fluidized bed calciners (FBC), and rotary kilns. The final alumina product is then transported to aluminium smelters. The aluminium industry is discontinuing rotary kilns in favour of stationary calciners (GSC and FBC types), which consume about 33% less energy (3.0 GJ/ton alumina compared with 4.5 GJ/ton alumina). The calcination step requires about 25% of the total energy in the Bayer Process.

Aluminium electrolysis: The Hall-Héroult Process

The Hall-Héroult (H-H) process for electrochemical reduction of alumina to aluminium was first patented in 1886, and it is still the main method of aluminium production today. Electrolysis takes place in a H-H cell: typically, a shallow rectangular steel basin 9 to 18 meters long, lined with carbon. In order to keep various materials molten, the cells operate at around 950-960°C. Inside the cells, a molten cryolite (Na_3AlF_6) electrolyte or "bath" serves as the conductor for the electric current running through the carbon anode to the positively charged surface of newly formed molten aluminium on the carbon lining (the cathode). Aluminium fluoride (AlF_3) is added to the solution to maintain optimal chemistry and lower the electrolyte's freezing point.

Beneath the carbon lining, steel bars pick up the electric current and take it to the next cell. Long rows of cells are connected in an electrical series (pot-line), sometimes up to around 400 cells. Automatic feeders continuously add alumina to cells, which dissolves in the molten electrolyte. As the electrical current passes through the solution, the dissolved alumina is split into molten aluminium ions and oxygen ions. The oxygen consumes the carbon in the anode blocks to form CO_2 .

Molten aluminium produced at the cathode surface is regularly removed by siphon from the top of the cell.

Operating Temperature: The molten bath chemistry is a major determinant of the temperature at which a H-H cell operates (typically 950-960 °C). The temperature affects the electrical resistance of the bath and thus the total cell voltage. A lower cell temperature also reduces the solubility range for alumina, decreasing cell operating efficiency.

Anode Effects: Current H-H cells are susceptible to anode effects, which are triggered by depletion of the alumina concentration. When this concentration becomes too low for normal cell operation, an anode effect occurs, characterized by

formation of carbon monoxide, perfluorocarbons (PFCs) and smaller amounts of CO₂. The bottom surface of the anode becomes covered by a gas film, leading to high voltages, typically 30 to 40 V (compared with usual 3.5-4.5 V). The smaller the anode surface immersed in bath, the higher the anode effect voltage. Anode effects thus lower cell operating efficiency cause a spike in energy requirements and evolve potent GHGs.

Electrolysis through the H-H process is by far the most energy-intensive step of aluminium processing, requiring about 13,000 kWh/t (47 GJ/t) in best-practice.

Carbon Anode

Production

The overall reaction takes place at the bath-metal interface as the reduction of alumina and the oxidation of the carbon anodes, producing pure aluminium and CO₂. Over time, the carbon anode is consumed; anodes must be replaced about once per month.

Currently, all new aluminium smelters use pre-baked anodes, named because baking bonds the calcined petroleum coke and coal tar pitch together. Anode production is itself an energy-intensive process, require about 444 kWh/t (1.6 GJ/t) under best-practice conditions.

Anode-Cathode Distance

The anode-cathode distance (ACD), the distance between the electrode surfaces in a given H-H cell, averages around 4-5 cm. The ACD is one of the main determinants of the voltage necessary for the current to pass through the bath and drive electrolysis. Voltage, in turn, determines electrical energy requirements (with a constant amperage cell operation). Lower ACD reduces voltage, but if the surfaces contact, the cell will short circuit.

Magneto-hydrodynamic (MHD) forces in the cell cause the surface of the molten aluminium to deform, and in some cases, undulate, so the ACD must be wide enough to accommodate this motion.

Downstream: Casting, Rolling, and Extrusion

The molten aluminium produced from the H-H process is typically cast into ingots, which are then transported to other processing plants to be transformed into final products.

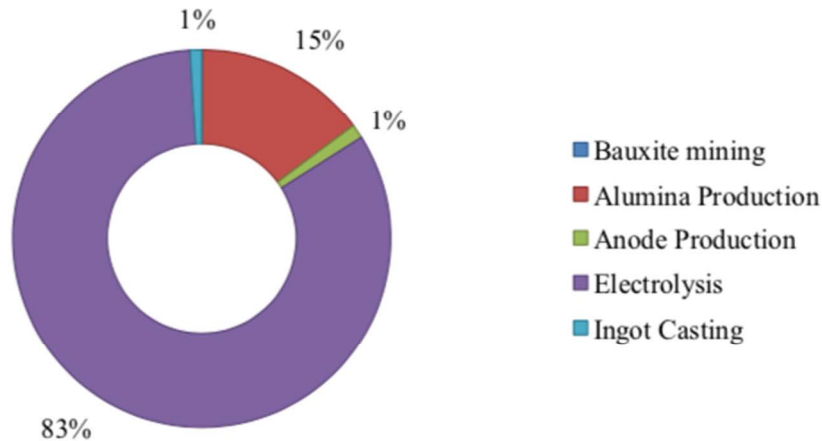
- Aluminium foundries may re-melt the ingots to produce alloys, which are then cast into the required shapes for consumer or industrial products.
- The malleability of aluminium metal means it is also well-suited for rolling into thin sheets. Aluminium may also be extruded.
- Products may be further processed, such as coating or painting.

Casting, rolling, and extrusion mills consume fossil fuels for reheating the aluminium ingots, as well as electricity, leading to indirect GHG emissions. Best-practice energy intensity for this casting is estimated at 278 kWh/t (1 GJ/t).

Summary of primary aluminium

Of the main process stages, electrolysis via the H-H route is by far the biggest consumption stage (83%), with alumina production from the bauxite being the next (15%) as well as being the main generator of solid / effluent waste.

Figure 5.4 Energy consumption ratios of primary aluminium production



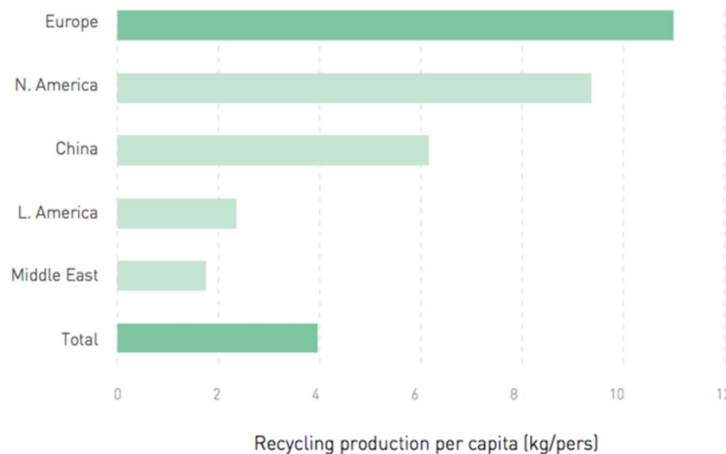
The aluminium industry has reduced its CO₂(e) emissions by 50% since 1990, but this is mainly attributed to: process improvements, a drastic reduction of PFC emissions (with their high GWP), and the closure of poorer performing smelters.

Secondary Aluminium Recycling

The production of secondary aluminium from scrap and recycled aluminium is becoming an increasing source of “fresh” metal. It offers the biggest “sea-change” opportunity to reducing energy and CO₂ emissions per tonne of fresh aluminium; reducing energy consumption per tonne by >90%. Recycling also offers substantial resource efficiency and other environmental benefits.

The key barriers are the ability to isolate and gather this recyclable material easier and the infrastructure to handle it.

Figure 5.5 Aluminium recycling by Global region¹⁶⁸



Recycling recovery rates within the EU are amongst the highest in the world; the average re-cycled metal in Europe is 40%, whereas globally the average is only 30%. In terms of tonnage per person, the EU is very good, although the EU is likely to be higher than most developing nations because it has higher consumption per capita as well as more available metal from applications coming towards the end of their serviceable life.

Between 1980 – 2013, the production of secondary aluminium increased by over 4 times (from approximately 1 Mt to 4 Mt/y).¹⁶⁹

5.2.1.2 Incremental CO₂-reductions with BATs

Alumina: Bayer process

1. Natural gas use as a fuel

Natural gas has the lowest specific emissions of all types of fossil fuels used in alumina refineries. The change from oil-fired boilers to gas-powered steam generators can reduce carbon emissions by 5%. This fuel switching is well established (TRL = 9).

2. Fluidised bed calcination

Circulating fluid bed (CFB) calciners were introduced in 1961 as an alternative to rotary kilns. They have much higher energy efficiency than rotary kilns, since the heat recovery is greater. Replacing rotary kilns with CFB kilns would cut energy demand by 60%, equivalent to 15% savings in the total Bayer process. CFB calciners are applicable only to smelter grade alumina. Investment costs are around EUR 20 /t Al, and the TRL is 9.

3. Tube digesters

Tube digesters can operate at higher temperatures using a molten salt heat transfer medium, enabling plants to operate at less than 10 GJ per tonne (BREF Notes); in

¹⁶⁸ "Recycling Aluminium – A pathway to sustainable economy", 2016

https://european-aluminium.eu/media/1712/ea_recycling-brochure-2016.pdf

¹⁶⁹ "The state of aluminium production in Europe", 2013,

http://europa.eu/rapid/press-release_MEMO-13-954_en.htm

fact, specific energy consumption (SEC) can be reduced to below 7.0 GJ/t

However, tube digesters are unlikely to be compatible with the layout of most existing primary EU plants. Plants with a double-stream digestion design using steam injection cannot convert to single stream digestion design without a total redesign and rebuild of the plant. Tube digestion is therefore virtually impossible to consider for existing plants for both cost and space reasons.

Globally, only 2 plants have tube digesters installed, one in the EU (Germany). It's TRL is 8.¹⁷⁰

4. Optimisation of the refining process

The refining process can be optimised in terms of energy consumption by implementing plant-specific measures. There are many factors, such as the technical configuration of the plant or the quality of alumina they produce, that limit the applicability measures such as:

- Plate heat exchangers: recover heat from the liquor flowing to precipitation. The potential heat recovery is higher than other techniques such as flash cooling plants. However, this technology is only appropriate for cases where energy from the cooling fluid can be reused.
- Selection of the bauxite: The quality of the bauxite ore impacts on energy consumption. Bauxite with higher moisture content carries more water, which needs evaporating. In addition, bauxites with high mono-hydrate content needs higher pressure and temperature in the digestion process, leading to higher energy.

The TRL for both is 9.

5. CHP and waste-heat co-generation

CHP can save 15% of primary fuel consumption of the plant. In an alumina refinery, cogeneration uses waste heat to produce steam for the refining process; plus, power for all the electricity needed for the refining process and support systems. In a combined site with both an alumina and aluminium plant, the heat produced can be used in the Bayer process and the electricity for the electrolysis.

Investment costs for a CHP plant are around EUR 242/t Al. Again, this is established technology, with a TRL of 9.

Electrolysis: Process Optimisation

Optimisation of the electrolysis process includes a range of hardware and software upgrades that can be installed on a smelter. The most notable upgrades include design upgrades to the smelter:

1. Magnetic compensation

An improved busbar design can compensate for magnetic fields that destabilise the alumina reduction process and increase electricity consumption. Laplace forces, created by the electric current and the magnetic field, are responsible for the motion of the electrolyte and the liquid metal. For an energy efficient process, it is essential that the flow is stationary. The design of the selection of busbar lengths and cross-sectional areas will balance the magnetic fields, thereby allowing the optimising of

¹⁷⁰ Author's note: realistically, only suitable for new plant or complete rebuilds, which would appear unlikely in EU for foreseeable future

the cell performance and the electricity consumption. The investment costs are around EUR 200 /t Al, but with no additional operational costs.

2. Improved hooding ventilation and suction

Improved hooding, ventilation and suction installations are beneficial for heat balance and energy use. Investment costs = EUR 120 /t Al, without additional operational costs. The exact nature of the upgrades differs by pot-line. These upgrades are typically implemented to some extent, and they are almost always possible. Total costs of optimisation can increase to around EUR 650 /t capacity, with modest operational costs of around EUR 1.8 /t capacity.

Electrolysis: Novel Physical Designs for Anodes

New physical designs for anodes can improve energy efficiency and complement inert materials. Several anode designs have recently been developed and commercialized:

- Sloped anodes and perforated or “slotted” anodes allow gaseous bubbles to safely circulate in the molten cryolite bath.
- Vertical electrode cells are a complementary design for the various electrode technologies.

These new anode designs offer the following benefits:

- Save 2.0 – 2.5 kWh/kg Al for slotted anode
- Can be easily combined with inert anode materials and/or wetted cathodes in retrofits
- Vertical cell designs reduce need for adjustments of anode position to prevent anode effect.

Slotted anodes are already commercially available, but to date with only low uptake (TRL is 8).

Electrolysis: Heat recovery from H-H off-gases

1. For the Bayer process

In theory, up to 22 GJ/t Al can be saved when retrieving the heat content of the off-gases (assuming 75 % heat exchange efficiency) of the H-H process, and then using it in the Bayer process to substitute fossil. However, in practice it will be less because some heat generated at the top of the pot is lost to ambient and the off-gas cannot be cooled below its acid dew point. A realistic savings potential is between 3-5 GJ/t and 8 GJ/t long term.

Clearly, this BAT is only applicable when the smelter and refinery are both located on the same site. There are very few combined Bayer and H-H sites, particularly in the EU. The TRL is 9.

2. Heat recovery and use elsewhere

A more widely applicable use of waste heat would be to use it in the local environment (e.g. via district heating system). There is no major technological or scientific hurdle to recovering heat. However, there can be some other commercial or practical barriers affecting the cost-effectiveness of the measure. The TRL of this

measure is 9.¹⁷¹

Anodes

1. Use of natural gas

As with the Bayer process, when natural gas is used to replace fuel oil, CO₂ and SO₂ emissions decrease. The estimated investment costs are about 13 M EUR for a 250 kt smelter, or EUR 52 /t Al capacity. The TRL is 9.

2. Recuperative or regenerative burners

In anode production, the application of enhanced furnace designs, with recuperative or regenerative burners, may produce fuel savings of 30-50 % with an investment cost of EUR 4-10/GJ and operational and maintenance (O&M) costs of EUR 0.2/GJ. Recuperative (30% savings) and regenerative (50% savings) burner systems are widely used in other high-temperature sectors. Regenerators typically have a much higher investment cost and are designed for higher temp and 24/7 operations. The TRL of these measures is 8-9.

3. Pre-baked Carbon Anodes

Point Feeder Pre-Bake (PFPB) allow better control of the electrolysis process and is the most commonly used technology. The use of PFPB cells with automatic multiple feeding points is considered BAT for primary aluminium production. Conversion to the state-of-the-art PFPB technology is the most accepted route for increasing operational and environmental efficiency for most systems; offering electricity savings of 10 to 30 %.

As well as electricity saving, the electrolysis process has a great potential to reduce the emission of perfluorocarbons (PFCs) – potent GHGs – formed during the anode effect, i.e. when the electrolyte becomes depleted of alumina. Over the past 20 years, this has been one of the largest contributors to reduced GHG emissions from aluminium smelting. The use of pre-bake technology has increased from 63 % in 1990 to about 90 % in 2010. It's TRL is 9.

Downstream aluminium: Transfer hot metal to alloying furnace

Direct casting of the molten metal, with embodied heat in the aluminium transferred to the alloying furnace. Best-practice electricity use is estimated to be 0.35 GJ/t aluminium ingot. The investment costs for a 250 kt cast house are around 180 M EUR, O&M costs for the same plant are around 17.4 M EUR.

This BAT is already implemented in most if not all EU cast houses (TRL is 9).

Downstream: Magnetic billet heating

This is explored in greater detail in the BAT – copper section (Section 5.2.2)

Secondary re-melting

Gathering and re-melting scrap aluminium is an established technology, although this can be improved.

Some of the BAT EE technologies related to secondary re-melting include:

¹⁷¹ For DHS: similar issues with any EFW DHS scheme

1. New de-coating equipment

This technology is applicable to the secondary aluminium industry that processes used aluminium, especially coated aluminium. An indirectly fired kiln and uses the energy released from volatile organic compounds to pre-heat the scrap to 480 °C before it goes into the melting furnace.

Investment cost estimated at EUR 40/t Al but the extra revenues from increased productivity are also EUR 40/t. In addition, this technology can save up to 50% on fuel costs for scrap pre-treatment (i.e. saves up to 362.5 MJ/t). TRL is 9.

2. Recuperative or regenerative burners

In secondary smelters, the application of enhanced furnace designs, with improved insulation, recuperative or regenerative burners, gas-air trim, etc can save up to 30-50 % of energy use at investment costs of EUR 4-10 /GJ and O&M costs of EUR 0.2/GJ. This is established technology, with a TRL of 8-9.

5.2.1.3 Decarbonisation with CCS

Carbon Capture Using Absorption Technologies:

CCS is more an end-of-pipe solution to collecting and removing CO₂ from point-sources with high CO₂ emissions. The actual process of capturing and sequestering the CO₂ is similar across all large CO₂ emitters: power stations, cement and glass manufacture, steel, etc. The sector specific challenge is to modify the existing process(es) so that one has fewer but larger/ higher concentrated point-sources of CO₂, so that capture is both easier and more cost-effective.

Absorbent-based carbon capture is a relatively well-characterized technology for major point sources of carbon emissions such as power plants but has yet to be applied to an aluminium plant. CO₂ emissions from electrolysis are dilute, with costs estimated at US\$100/tCO₂ + extra energy.

This route is unlikely to be commercially viable for primary aluminium makers using the H-H process. CCS from electrolytic cells has received very little attention; due to the inherent features of the effluents produced by primary aluminium smelters, current approaches for CCS cannot be applied in a straightforward way. Furthermore, if novel electrolysis routes are implemented which do not emit CO₂, CCS will be less viable.

For absorption-based CCS from aluminium electrolysis process, the TRL is 3-4.

Carbon capture and storage (CCS) applied to power plants

CCS may be practical for any fossil-fuel power-plants that generates electricity for servicing the Al process, but this is the same for any fossil-fuel power plant.

All on-site fossil-fuel powered plants operating in the aluminium sector in EU and Iceland are gas-fired CHP plants. Their exhaust gases can be cleaned with CCS technology, capturing up to 90 % of the CO₂ emissions from the gases. The costs of equipping a CHP plant with CCS technology at around EUR 425 /kW installed capacity. No additional operational costs are associated with this technique.

For this “classical” CCS on power plants, the TRL is 5-7.

5.2.1.4 Decarbonisation with novel techniques

Bauxite: Red mud treatment

This represents a relatively small energy-saving process, however, an important environmental consideration and an important enabling step to help make alumina production more economical and environmentally responsible.

Alumina generation from bauxite creates large quantities of a hazardous solid waste - red mud - with correspondingly high disposal costs. With some grades of bauxite, 2.5 t bauxite is needed to make 1 t Al_2O_3 + 1.5 t red-mud.

A novel EAF technology, Advanced Mineral Recovery Technology (AMRT), can smelt red mud without any pre-treatment, producing pig iron and viscous slag suitable for industrial mineral wool. The solid charge is fed into the 'arc zones' of each electrode, where flash smelting takes place. The red mud, with chemical exergy of 0.49 GJ/t Al, is replaced by saleable pig iron and mineral wool products, with total chemical exergy 6.32 GJ/t Al.

In total, the new proposed process for complete bauxite exploitation (for alumina, pig iron and mineral wool production) could increase the exergy efficiency from 3 % in the conventional Bayer Process to 9-13 %. It's TRL is estimated to be 3-4.

Perhaps more importantly, the process converts a hazardous waste into two viable co-products, also preventing accidental discharge into rivers/ marine or water table. It also offers a route for cleaning-up legacy red-mud.

Alumina reduction: Carbo-thermic Reduction

High temperature carbo-thermic reduction of alumina is the only non-electrochemical process that has shown potential for aluminium production to date. It is radically different to the current H-H process or the emerging Elysis process.

Carbo-thermic reduction reacts alumina with carbon at high temperatures (>2000 C) to form aluminium and CO. Compared to conventional H-H smelting, carbothermic reduction may have the following benefits:

- Reduces energy per unit Al by around 20-30%
- Reduce capital costs by 50% and lower operating costs significantly

To date, the different options examined have the potential to reduce capital investment by around 50 %. The estimated investment costs are EUR 3000 /t Al.

Once available, a carbothermic plant is likely to be the preferred option for new plants; however, this is not expected before 2050. The TRL is estimated to be 2-3.¹⁷²

Aluminium reduction from other raw materials: Kaolinite Reduction

Kaolin is an alumina-silicate clay. Kaolin reduction for aluminium production actually pre-dates the H-H process, although commercialisation was difficult, and the process is still at R&D stage. Compared to the current Bayer then H-H processes, the chlorination and reduction of kaolin clay could offer the following benefits:

- A new source of widely available and inexpensive ore

¹⁷² Although others claim the technology is at pilot phase, TRL = 5

- Faster and more efficient conversion in Al chloride production and reduction reactions, with overall energy savings of 12% - 46%
- Smaller cells with the ability to retain temperature and idle would allow Al producers to take better advantage of electricity demand response systems.

Perhaps equally importantly, this process could be good for the EU as the EU has plentiful supply of kaolin, rather than relying on imported bauxite or aluminium metal. This is still considered at the R&D stage and has a TRL of 1-2.

Electrolysis: Inert electrodes

Carbon electrodes have been in use ever since the start of the Hall-Héroult (H-H) process, over 130 years ago. Inert electrodes would replace the energy-intensive-to-make (and direct CO₂ emitting) carbon electrodes, so would be a step change to the process. Benefits include:

- Energy savings of 3-4% within a modified H-H cell
- Reducing cost of production and replacement of consumable carbon anode. Capital costs for inert anodes are estimated between 10%-30% lower than conventional anodes
- Eliminating GHGs (HFC, PFC, CO₂) produced by electrolysis with carbon anodes. Instead, the inert anodes produce oxygen.
- Improving H&S by eliminating need to regularly replace carbon anodes.
- Improving plant operating efficiency by eliminating anode effects (PFCs and HFCs emissions – both substantial high GWP GHGs)
- For inert anodes with zirconia tubes, reducing cell energy losses by > 60%

Materials that have been considered for inert anodes include metals, ceramics, and cermets. This process is already at the demo stage but, given recent developments – see Elysis below - is likely to have accelerated uptake. The TRL is estimated to be 5.

Electrolysis: Wettable Cathodes

'Wetting' refers to improved electrical contact between molten aluminium and the carbon cathode. A completely wetted cell lining that was also inert to the cell bath would allow:

- The anode to be brought closer to molten Al without high magneto hydro-dynamic (MHD) instability
- Molten aluminium to be drained out of the anode-cathode spacing;

There are several concepts for wetted cathode and draining cells, compared with a traditional H-H cell. A good example is TiB₂ composite cathodes. Benefits:

- Reducing energy consumption by 20%, or 3.05 MWh/t Al, by lowering the anode-cathode distance (ACD). This equates to EUR 152.5 /t Al (@ EUR 50 /MWh(e)).
- Extending cell life by preventing contamination and lowering the formation of undissolved alumina sludge
- Reducing the amount of toxic, spent pot-liner waste

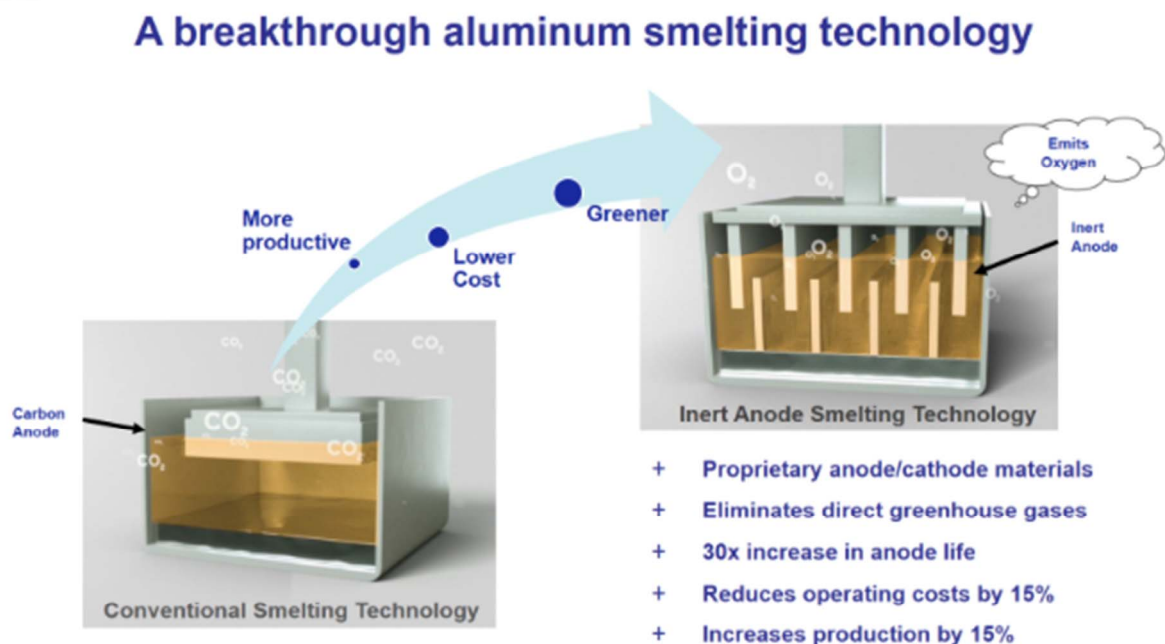
Again, this is likely to have an accelerated uptake - see Elysis below.

Electrolysis: The Elysis process

In May 2018, Alcoa and Rio Tinto announced the World's first "carbon-free"

aluminium smelting process, called “Elysis”. In effect, it is the commercialisation of a combination of inert electrodes and wetted cathodes.

Figure 5.6 Main differences between current H-H primary aluminium processing and Elysis¹⁷³



The emerging technology is currently producing metal at the Alcoa Technical Centre, near Pittsburgh, USA.

Alcoa and Rio Tinto launched a new joint venture (JV) for larger scale development and commercialization of the process. The development is being supported by Alcoa, Rio Tinto, the Government of Canada, the Government of Quebec and Apple, with a combined investment of \$CAN188 M.

Removing the H-H process emissions, brings down emissions by 55%, potentially by 72% if the electrolysis process is powered through renewable means. To put the impact on GHG emissions into perspective, it has been estimated that, in Canada alone, the technology could eliminate the equivalent of 6.5 Mt/y CO₂ equivalent metric tonnes of greenhouse gas emissions

The plan is that the new JV company will:

- Create a technology package planned for sale beginning 2024
- Further develop the technology so it can be licensed for retrofit at existing smelters or used to design and build new facilities.
- Also sell proprietary anode and cathode materials, which will last more than 30 times longer than traditional components.
- Instead of CO₂, the process emits oxygen and replaces all point-source greenhouse gas emissions – CO₂, PFCs and HFCs.

Some links relating to the Elysis process is provided in the footnotes¹⁷⁴. The

¹⁷³ <https://www.alcoa.com/global/en/what-we-do/elysis/default.asp>

¹⁷⁴ <https://elysistechnologies.com/en#unprecedented-aluminium-partnership>
<http://investors.alcoa.com/news-releases/2018/05-10-2018-192208334>

technology is expected to become commercially available around 2024 and has a TRL estimated to be 6.

Electrolysis: Application of a dynamic AC magnetic field

In the H-H cell, one needs to maintain a minimum distance between anode and cathode to avoid short-circuiting. However, the greater the electrode separation, the greater the cell resistance, which in turn consumes more electricity.

The application of a dynamic AC magnetic field significantly suppresses ripples in the molten aluminium, enabling smaller electrode separation and therefore lower electricity use. Energy savings achieved with this technique are between 5-20%. The investment costs for a 250 kt smelter are around 20 M EUR, i.e. EUR 80/t Al,

It is worth noting that this technology would be superseded if wetted drained cathodes were successfully implemented. It's TRL is estimated to be 3-4.

Electrolysis: Lower temperature, while maintaining stable operations

In current practice, electrolysis is performed at about 950 C, far above the melting point of aluminium (680 C).

Theoretically, reducing the temperature to around melting point should decrease electricity by 1.0-1.5 MWh/t, although in reality savings are likely to be around 0.7 MWh/t (5%). Also, energy from the superheated metal is generally used to re-melt pre-loaded scrap in the casting house, benefitting from its "free" energy.¹⁷⁵

The extra operational cost of decreasing the electrolyte temperature by optimising its composition is about EUR 75/t.

This technique is only now becoming available on the market, but to date no smelters use the lower electrolyte temperature. The TRL is 7.

Electrolysis: Multipolar Cells

Existing Hall-Héroult (H-H) cells can have multiple anodes but only one horizontal cathode, which is both capital and energy intensive. Multipolar cells (currently at R&D) offer:

- Only work with inert anodes, due to the need for a stable ACD, which in turn offer longevity (3 y rather than 1 month for C electrodes), plus emits O₂ rather than CO₂ (and other GHGs) as part of the process;
- Offer EE savings of around 40%, by: operating at lower temps - around 700°C, working at higher current densities, and allowing better control of heat loss;
- Improved circulation of electrolyte and separation of chlorine and Al product.

This is still at the R&D stage and has a TRL of 2.

Electrolysis: Ionic Liquids

Ionic liquids are a range of non-conventional organic solvents, electrolytes, and molten salts that have low melt temperatures, which could replace H-H electrolysis,

<https://pm.gc.ca/eng/news/2018/05/10/alcoa-and-rio-tinto-announce-worlds-first-carbon-free-aluminium-smelting-process>

¹⁷⁵ Similar to loading scrap steel into the basic oxygen furnace to capture the chemical heat.

allowing the electrolysis to happen closer to room temperature rather than 1000 C.

This process is still only at R&D phase and process has several substantial difficulties to overcome; nonetheless offers potential energy and emissions reductions. Compared to conventional aluminium technologies, ionic liquids could offer:

- 30%-85% of energy compared to H-H smelting, due to low-temperature
- Reduce polluting gases, like CO, and reduced solid wastes from spent linings
- Increase bauxite-to-alumina conversion efficiency

It appears that ionic liquids could be more suitable for electroplating products with Al rather than producing large quantities of primary Al. The TRL is estimated to be 1-2.

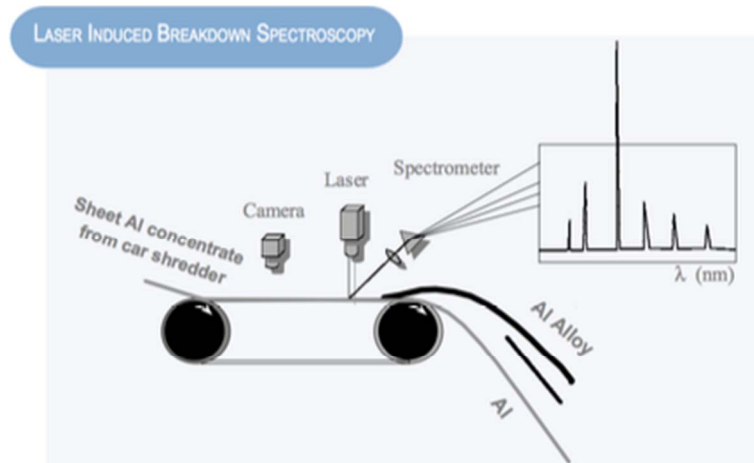
Aluminium recycling: Emerging Technologies

As mentioned already, recycling of aluminium (and other non-ferrous metals, such as copper) offers some of the largest energy-saving potential. Secondary Al from recycled sources consumes about 6% of the energy compared with primary Al.

However, aluminium comes in a variety of different grades and quality (as well as impurities), which act as a major cost barrier. Economic scrap collection and sorting is key. Physical sorting of scrap metal is more economical than melt refining technology. Potential low-cost techniques for economic aluminium sorting include:

- Fluidized bed sinks float technology
- Colour etching then sorting
- Laser induced breakdown spectroscopy (LIBS). Currently, this appears the most promising high volume/ high speed process; it is currently at demo stage.

Figure 5.7 Laser induced breakdown spectroscopy



Main benefits:

- Secondary aluminium energy savings of over 12% over current secondary production techniques
- Potential life cycle cost savings due to improved secondary aluminium quality

- Any successful, cost-effective technology would help improve overall recovery, plus act as a disincentive for EU to export > 1 Mt/y aluminium scrap (and growing) to emerging economies, where labour sorting predominates.

The TRL is estimated to be 5.

Aluminium Mini Mills

Currently, most secondary aluminium is produced in ingots that are then shipped to rolling mills to be made into final products. Mini mills are an integrated design that eliminates several energy-intensive re-heating / cooling steps. They can be located nearer population centres – making better use of the scrap source material – rather than shipping to (say) China or India for physical sorting.

The technology is claimed to offer 84% energy saving compared to current scrap-to-product recycling processing as well as substantial raw material savings.

This is still at small scale pilot stage and has a TRL of 6.

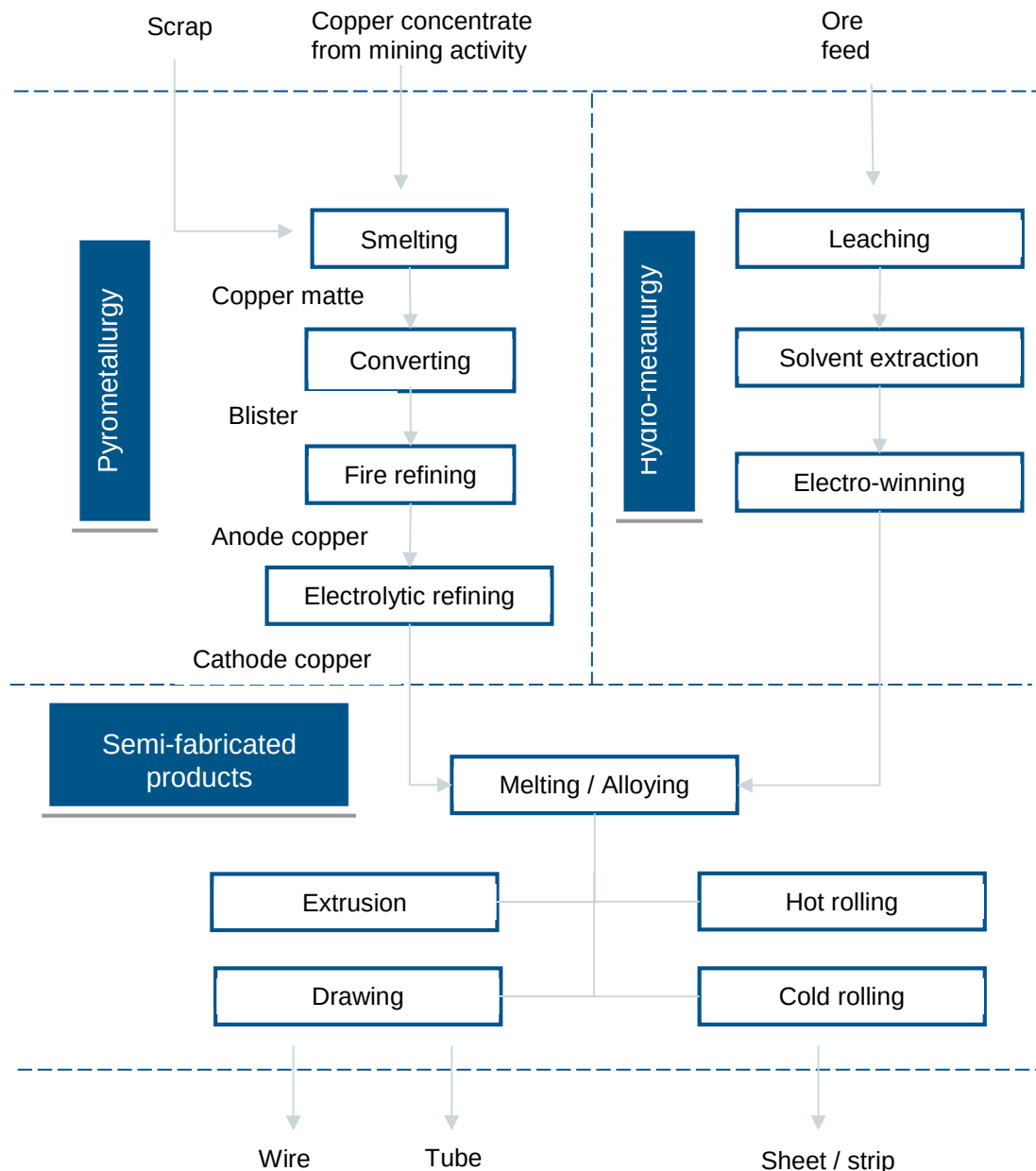
5.2.2 Copper

5.2.2.1 Conventional production methods

Overview

Figure 5.8 provides an overview of the key processes in primary and secondary copper production. There are two main routes in production of primary copper; the pyro-metallurgical or hydro-metallurgical route. Approximately 80% of primary copper is produced through pyrometallurgy process and the remaining 20% with hydro-metallurgy process. The hydro-metallurgical route is particularly suitable for ores which are difficult to concentrate by conventional means and does not contain precious metal.

Figure 5.8 Overview of primary and secondary copper production (source: ECI)



Pyrometallurgy: Smelting¹⁷⁶

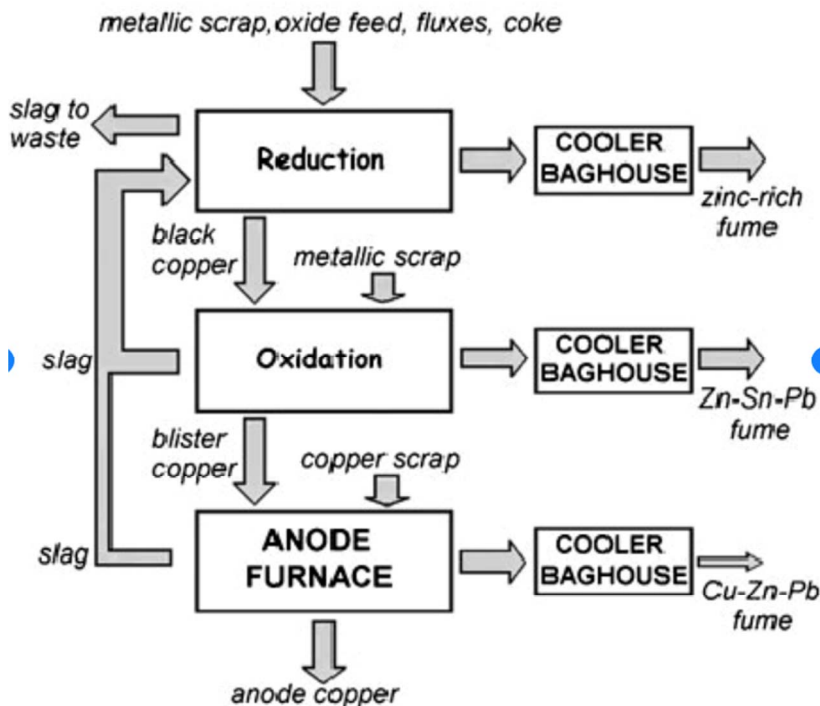
Copper ore typically contains < 1% copper mineral. The ore is extracted using traditional methods of underground or open pit mining¹⁷⁷. The ore is crushed, screened, and washed. The finer sulphide ore is then enriched. Crushed ore is added to a reaction vessel containing pine oil and coalescing agent such as xanthate, and air is injected to the vessel. The concentrated ores float to the top of the vessel where the froth is skimmed off, calcified and crushed to fine ore containing about 25% copper.

¹⁷⁶ <https://www.brighthubengineering.com/manufacturing-technology/68414-smelting-copper-from-ore/>

¹⁷⁷ the later accounting for 90% of the ore used in smelting

These ores are then generally thermally treated in a reducing atmosphere to generate copper metal. There are several methods of copper smelting, the popular ones being reverberatory smelting and oxygen flash smelting.

Figure 5.9 Simplified process flow for copper smelting¹⁷⁸



In the reverberatory furnace, fossil fuel and oxygen fired burners melt the copper ore. The furnace has a tapping point for extracting the molten copper and slag. The tapped copper, which is about 65% purity, is then transferred to a converter furnace, whilst the slag is either recycled or discarded to a slag heap. The process generates a lot of heat, so a waste heat boiler is often incorporated to recapture and reuse the heat for upstream and downstream processes.

The molten copper passes to the converter furnace, where it is injected with oxygenated compressed air. The oxygen reacts with the sulphide ore, producing copper sulphate and converting the copper ions to “blister” copper of over 98% purity. The converter furnace is tilted and the blister copper passes onto an anode furnace.

Anodes then undergo electrolytic refining: suspending an anode in a tank containing copper sulphate and a plate of pure copper effectively acting as a cathode. A current is passed through the solution and the copper ions are stripped from the anode and deposited on the cathode, further refining the copper to >99.5% purity, with impurities falling to the bottom of the tank.

SO₂ gas produced in the furnace is extracted by centrifugal fans and discharged through ducting to the acid plant, where it is processed and converted to sulphuric acid being used in smelting and ore processes, any remaining acid being sold.

¹⁷⁸ From: https://www.researchgate.net/figure/Simplified-flow-sheet-of-black-copper-smelter-process-secondary-copper-smelting-59_fig3_261181219

Pyrometallurgy - Recent activities

EU-based copper producers have reduced their unit energy consumption by 60% since the 1990s¹⁷⁹, largely by:

1. Technology improvements; including:
 - Flash smelting technology.
 - Waste heat recovery.
 - Renewal of electrical equipment – particularly motors
 - New or adapted furnaces.
2. Several of these are described in the BAT section, below.
3. Use of renewable energy rather than grid-power, generally hydro, solar PV, wind or other power generation.
4. Increased recycling and the “circular economy”, discussed further below.
5. Environmental emissions abatement, particularly SO₂ emissions.

Hydro-metallurgy

The hydro-metallurgical process is carried out with much lower temperatures, therefore eliminating the production of sulphur dioxide emission, but produces effluent which must be treated.

Crushed ores are mixed with a leaching solution, typically sulphuric acid, which dissolves the copper and leaves a residue of precious metals. The leach solution then undergoes a purification process to remove dissolved iron and other impurities and concentrating of copper in smaller volumes by the solvent extraction process. The stripped solution, containing mainly copper sulphate, is then sent to the electro-winning stage. Electro-winning consists of the recovery of copper metal from the stripped solution (electrolyte) in a unique electro-winning cell. As current is passed, copper is then deposited at the cathode forming copper cathode.

Recycling copper

As with aluminium and other metals, re-use of end-of-life copper is seen as perhaps the biggest opportunity for making “order-of-magnitude” energy-savings per tonne of metal. Recycling also offers substantial resource efficiency and other environmental benefits. Again, the key barriers are the ability to isolate and gather this recyclable material easier and the infrastructure to handle it.

Copper produced from recycled scrap uses 20% of the energy required for primary metal. [Note: this figure is considerably higher than for aluminium, partly because the energy to generate primary aluminium is very high (compared with copper), and partly because the specific heat capacity and latent heat of solidification for copper is high (meaning more energy is required to re-melt a tonne of copper).]

Europe’s demand for copper is increasingly met by recycling. According to the International Copper Study Group (ICSG), about 50% of the copper used in Europe now comes from recycling, largely from industrial and consumer waste, such as: pipes, brass, vehicles and old electrical appliances. In 2014, 2.1 million tons of copper were reused in Europe, coming from end-of-life products and directly-

¹⁷⁹ EC Science for Environmental Policy: Issue 470, Sep 2016: “Copper demand to increase up to 341%”: http://ec.europa.eu/environment/integration/research/newsalert/pdf/copper_demand_increase_up_to_341pc_2050_470na1_en.pdf

recycled factory waste. The EU has three production sites where 100% of the raw material is scrap. However, a lot of the collected copper is exported; in 2014, net exports from EU were approx. 0.9 Mt scrap (around 20% of EU total copper demand).¹⁸⁰

Copper recycling and waste management have become an important part of the supply chain, keeping resources local, creating local jobs, saving on landfill and incentivising recycling of other materials. Copper is present in modern equipment, such as: electrical installations, engines, solar systems and smart buildings.

- a computer contains = around 1.5 kg of copper,
- a typical home = about 100 kg: boilers, water tanks and piping, electrical equipment and motors, much of which is recycled,
- a wind turbine = 5 tons, although very little of this has been recycled to date.

5.2.2.2 Incremental CO₂-reductions with BATs

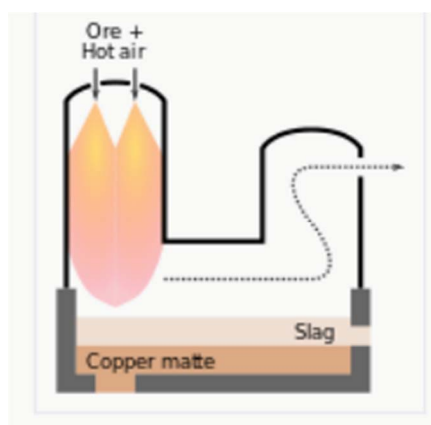
Copper companies generally agree that the existing production process have almost reached its technological plateau. Nonetheless, the following section presents some remaining potential opportunities.

BAT Smelting: The Outokumpu process/ flash smelting

The Outokumpu process¹⁸¹, also known as “**flash smelting**” is a smelting process for sulphur-containing ores, including copper bearing chalcopyrite. The process was first applied in Finland in 1949 for copper ore and is by far the most frequent of the more modern “flash-smelting” technologies introduced over the past 50 years.

Flash smelting with oxygen-enriched air (the 'reaction gas') makes use of the energy contained in the concentrate to supply most of the energy required by the furnaces. The concentrate must be dried before it is injected into the furnaces and, in the case of the Outokumpu process, some of the furnaces use an optional heater to warm the reaction gas to 100–450 °C.

Figure 5.10 Outokumpu process schematic



A second flash smelting system, developed by INCO, has a different concentrate feed design compared to the Outokumpu flash furnace. This was primarily designed for nickel, although it can also be used for copper. The Inco flash furnace has end-

¹⁸⁰ European Aluminium, Eurostat, CWT, EEA

¹⁸¹ https://en.wikipedia.org/wiki/Flash_smelting

wall concentrate injection burners and a central waste gas off-take, whilst the Outokumpu flash furnace has a water-cooled reaction shaft at one end of the vessel and a waste gas off-take at the other end.

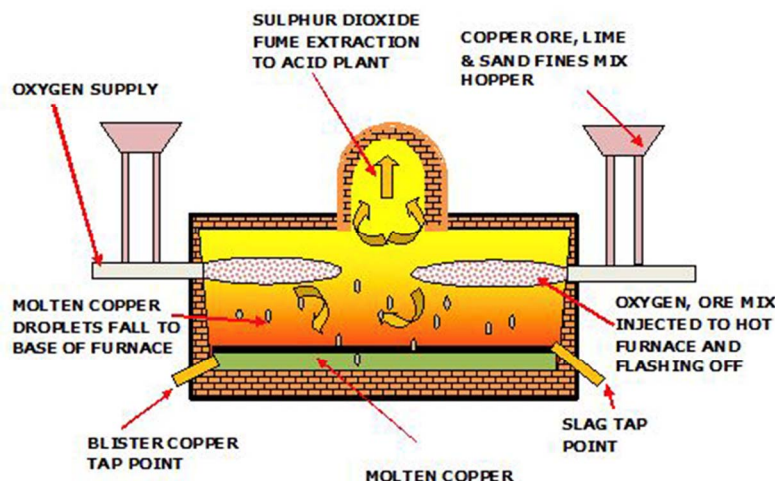
The reactions in the flash smelting furnaces produce copper “matte”, iron oxides and SO₂. The reacted particles fall into a bath at the bottom of the furnace, where the iron oxides react with fluxes, such as silica and limestone, to form a slag.

In most cases, the slag can be discarded, and the matte is further treated in converters to produce blister copper. In some cases where the flash furnaces are fed with concentrate containing a sufficiently high copper content, the concentrate is converted directly to blister in a single Outokumpu furnace, removing one of the energy-intensive production stages. TRL is 9.

BAT Smelting: Using Oxygen Flash Technique

Oxygen flash technique is a relatively new and efficient method of smelting copper. The operation takes place in a preheated furnace. A fine mix of copper ore, sand and limestone are injected by compressed oxygenated air, prompting immediate endothermic combustion at 1100°C, without using any other fuels.

Figure 5.11 Smelting Using Oxygen Flash Technique

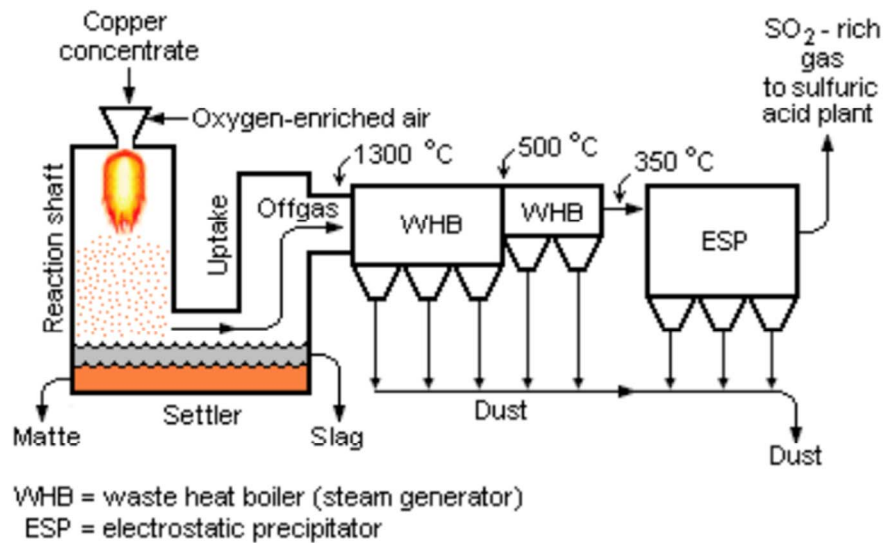


The copper ore becomes molten copper droplets, which fall to the bottom of the furnace, forming a molten copper layer with a slag floating on top of it. The molten copper is tapped and sent through the same processes as the reverb smelted copper, except it eliminates the converter stage, as the metal has been already converted to blister copper in the flash furnace. The TRL is estimated to be 8.

BAT: Waste heat recovery boilers

Copper-bearing concentrate is fed, along with oxygen-enriched air, into the reaction section of the smelter. The flame is maintained by the combustion of sulphur contained in the copper concentrate feedstock with oxygen.

Figure 5.12 Waste heat recovery boiler for power-generation



The hot combustion exhaust gas is used to exchange heat with pressurized water and thereby generate steam via *waste heat boilers* (WHBs). These are fairly conventional units and are used across many industrial sectors to generate power, which can then be used across the site.

WHBs typically generate saturated steam at a pressure of about 40 to 60 bar and a temperature of 250 to 285°C. The first WHB is the *radiant section*, the second is the *convection section* and a single steam drum serves both sections.¹⁸²

The combustion off-gas contains between 20 – 60% SO₂ at a temperature of about 1300 C. It also contains small solid particles (dust). About 60-65% of the dust is periodically removed from the heat exchange tubes by spring hammers; the remainder is removed by an electrostatic precipitator (ESP), after the gas has been cooled to a temperature that can be tolerated by an ESP, i.e. < 350C. The dust is subsequently recycled back into the reaction shaft feedstock.

Downstream: Magnetic billet heating¹⁸³

Magnetic billet heating is a simple and energy efficient heating process of pre-made metal billets, including aluminium and copper billets. Billets can be rapidly brought to a uniform temperature, thus damage caused by surface overheating is prevented.

With conventional induction heating billet are placed inside a copper coil, which is powered by an AC current to generate an electromagnetic field which changes direction over time. The field induces eddy currents in the workpiece that heat the billet due to electrical resistivity. The coil must be water cooled to prevent it from melting; this is the main source of energy losses in conventional AC induction heating systems. Typically, overall system efficiency is 50 – 60%.

¹⁸² The schematic does not show the steam drum or the various heat exchange tubes in the WHBs, but they are similar to many conventional high-temperature WHR boilers

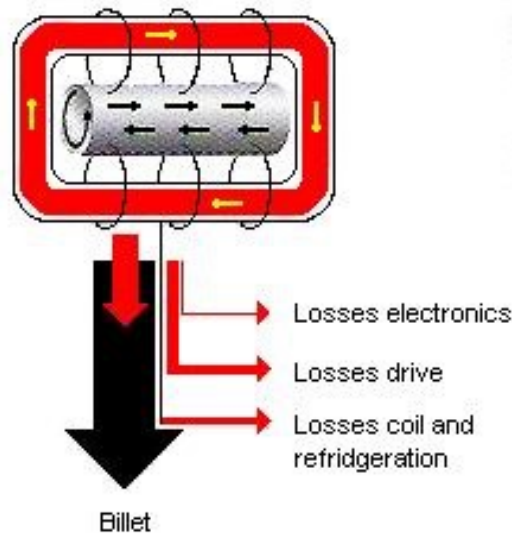
¹⁸³ "Magnetic Heating Of Billets", 2010,

http://home.zcu.cz/~tesarova/IP/Proceedings/Proc_2010/Files/019%20IP2010%20Bublik.pdf

"Has Magnetic Billet Heating got what a new standard solution needs?", 2010,
www.bueltmann.com/clipping-report.html%3Ffile%3Dtl_files/bueltmann/downloads

DC Magnetic Billet heating consists of four main components: superconducting magnet, refrigerator, motor and heating chamber. The main component is the superconducting magnet. This is kept at its operating temperature by the refrigeration system. Billets rotate in two thermally insulated heating chambers. No component in the heater is subjected to significant temperature increase, vibrations or any other mechanical stresses.

Figure 5.13 Magnetic billet heating schematic



Benefits:

- **Low frequencies.** Power grid frequency AC induction heaters induce eddy currents close to the surface of the workpiece. Deeper penetration can be reached by using lower frequencies or more powerful magnetic field.
 - Energy penetration is three times as deep with Magnetic Billet heating as with AC induction heater.
 - Heating is much more uniform, faster and does not risk melt the heater.
- **Low maintenance requirements.** Compared with conventional AC heaters the maintenance requirement of the machine is minimal due to a simple mechanical design.
- **Reliability.** No part of the heater outside the heating chamber ever exceeds 70°C; most parts stay below 50°C.
- **Productivity.** Increase of productivity amounts to an average 25% across a variety of profiles and the
- **Costs.** Heating costs were reduced by 50% compared with conventional AC heating. Achieving these results did not involve any significant additional expense.

The combined economic effect of energy savings and productivity improvements resulted in a payback period of less than two years. The TRL is 8-9.

5.2.2.3 Decarbonisation with CCS

Carbon Capture and Storage techniques have yet to be researched or developed specifically for the copper industry. These could be applied when looking at the primary smelting process in pyrometallurgy. Relying on high temperatures generated by fossil fuels to smelt, the fumes of these smelters could be captured under a CCS framework. No specificities of the industry would enable CCS to

develop, hence the incorporation of the technology would depend on its development in other industries, as it would become mainstream for general combustion streams, it could be applied to copper industry.

5.2.2.4 Decarbonisation with Novel techniques

Copper extraction using electrolysis¹⁸⁴

In 2017, MIT researchers developed a route to selectively separate pure copper and other metallic elements from sulphur-based minerals, using molten electrolysis.

The process is broadly similar to the aluminium H-H cell. The research found a method of forming liquid copper metal and sulphur from an electrolyte composed of barium sulphide, lanthanum sulphide, and copper sulphide¹⁸⁵. Electrolysis decomposed sulphur-rich minerals into pure sulphur and extracted three different metals at high purity: copper, molybdenum, and rhenium.

This one-step process greatly simplifies metal production. It yields > 99.9% pure copper, which is equivalent to the best current copper production methods but without having undergo multiple (energy intense and polluting) process stages. Furthermore, it is more energy efficient and eliminates toxic by-products such as SO₂.

The new work built on earlier electrolysis techniques and doubled the overall efficiency for electrolytic extraction of copper, from 28% to 59%.

If it could be scaled-up to pilot, demo then industrial sizes, the ideal would be to run a continuous process; maintaining a constant level of liquid copper and then tap this out of the electrolysis cell. [A lot of similar engineering has already gone into that for the aluminium industry, so the potential to apply that process is good.]

Further refinements:

- The aluminium electrolysis systems operate at 95% faradaic efficiency, so clearly there is room for improvement from the reported 59% copper efficiency.:
- To further improve cell efficiency:
 - modify the cell design to recover a larger amount of liquid copper.
 - Further tune the electrolyte, adding sulphides other than barium or lanthanum.
 - Further refine the temperature and chemical mixture

Costs: no information on potential cost, and TRL is estimated to be 2-3.

In-situ copper control

Copper liberation is a part of the electro-refining process that is often overlooked. Liberation is carried out for two purposes:

- It is an integral part of the electrolyte impurity control process and
- to control the copper concentration in the tank

¹⁸⁴ <http://news.mit.edu/2017/new-way-of-extracting-copper-0628>

¹⁸⁵ Experiments were conducted at 1,227 °C, about 150 °C above the melting point of copper, a temperature commonly used for copper extraction.

With traditional liberation, the B-grade copper is usually circulated back to the smelter, wasting the electrical energy used to produce then recycle it. A patent-pending concept to improve copper concentration control in copper electrorefining was registered in 2017.

Thermally regenerative batteries:

Copper could be used in new fashions to reduce global energy footprint. Large amounts of low-grade waste heat ($<130^{\circ}\text{C}$) are currently released during many industrial, geothermal and solar-based processes. Thermally regenerative batteries (TRBs) can convert this waste heat into electrical power. Thermally regenerative ammonia-based batteries (TRABs) as well as acetonitrile-based batteries, based on copper electrodes, have been developed to produce electrical current from the formation of copper-ammonia or copper-acetonitrile complex, using waste heat to regenerate the process.¹⁸⁶

Alternative fuels or carriers

- The copper smelting process could be split into a thermal component from electric source and reducing agent from biocoke. This is broadly similar to the electrification of primary steel making. There was little information on this potential route
- Given the high temperatures needed to make copper, biofuels are not currently seen as good candidates as replacement thermal energy sources. With the development of new biofuels for jet fuel, this limitation may be overcome in following years.
- Hydrogen gas as a reducing agent during smelting is not seen as candidate as it embrittles copper

¹⁸⁶ <http://cubes.leonardo-energy.mobi>

6 Refineries

6.1 Core Products

Refinery processes are downstream production processes for fossil fuels. After having extracted fossil resources from the earth, these are generally refined to create more valuable products. Solid fossil material like coal can be converted to coke. Crude petroleum oil is not very useful as it is. It is refined to separate the variety of chemicals within the crude to useful products, such as propane, diesel, kerosene, asphalt, etc.

6.1.1 Coke product

Coke is produced by processing low-ash, low sulphur bituminous coal. Pulverised coal is heated in a coke oven, in the absence of oxygen, at high temperatures (1200-1300°C). The necessary heat is provided by external combustion of fuels and recovered gases. Coke is the solid material remaining in the oven. There are approximately 1,900 coke oven installations in the EU.¹⁸⁷

6.1.2 Coke value chain

About 90% of the coke consumed in the EU is used in the production of iron from blast oven furnaces. The remainder is used in iron foundries, non-ferrous smelters, and the chemical industry. Since the 1990's, production has been declining, with capacity closures at their peak in 2009-10 due to low commodity prices, with China now accounting for over 70% of global coke production.¹⁸⁸ Furthermore, despite coke being important to the iron production process, to increase cost effectiveness steel-makers are adopting new technologies that aim at reducing the quantity of coke required. For example, injecting pulverised coal, waste plastic, natural gas or oil directly injected in blast furnaces rather than in the coke oven.

6.1.3 Petroleum products

Refined petroleum products are derived from crude oils through processes such as catalytic cracking and fractional distillation. The type of crude oil a refinery can process depends on the processing units operated (i.e., complexity) as well as the desired product slate. All refineries have crude oil fractional distillation, where crude oil is distilled into a number of fractions; e.g., petroleum gases, light and heavy naphtha, asphalts and residue. However, depending on the level of the refinery's complexity, these fractions can be upgraded to commercially viable products through additional processes; such as hydrodesulphurization and hydrotreating to produce fuels with reduced sulphur content; catalytic cracking for higher yields of kerosene and gasoline; and catalytic reforming to increase the octane number of the gasoline.

¹⁸⁷ <https://www.quandl.com/c/energy/consumption-by-use-coke-ovens-un-by-country>

¹⁸⁸ Jones Andrew; 2013; *Coke Markets – European Perspective*; Presentation at the Eurocoke conference, April 2013

In 2012, there were 96 petroleum refineries in EU-28.¹⁸⁹ Of these, approximately half of Member States have “complex” refineries, with the remainder considered “simple”.¹⁹⁰ The level of complexity defines whether a refiner can effectively respond to changes in product supply and demand by shifting its product slate. For example, refineries may produce more gasoline during the spring and summer months when demand is high, than they do during the winter when demand for heating oil is high.

6.1.4 Petroleum value chain

The composition of the distillate will vary depending on the crude oil used. On average, the split is approximately 19% heavy oils, 40 % distillate (mainly jet fuel and diesel), 31% gasoline and 10% light gas.

The heavy oils extracted from refineries are composed of the largest molecules containing the most carbons atoms per molecule. These can be liquid or even solid at room temperature, such as: wax, asphalt, lubricating oils and other greases).

The distillate fraction is composed of a mix of intermediate components such as heating oil (generally at 14 to 20 carbon atoms per molecule), diesel fuel (at 10 – 15 carbons per molecule) and Kerosene also known as jet fuel (typically from 8 to 16 carbons per atom). Kerosene is the principle component for aircrafts, whereas diesel is used heavily to power automobiles, currently powering 41.2% of vehicles in the EU.

The most obvious of these components is gasoline. A transparent liquid fuel tailored to the right octane to be stable in a tank, but easy to spark-ignite in an internal combustion engine. The typical gasoline content consists of hydrocarbons between 4 and 12 carbon atoms per molecule, hence, is one of the lighter elements of the distillation process. It is the main component in the fuel for petrol cars, which currently are 55.6% of all vehicles in the EU. It is often supplemented in the fuel mix with ethanol.¹⁹¹

The light gases mixture is composed mainly of propane, butane, ethane and methane. These can be burned on site to further the refinery process, separated and sold separately as fuel, or sold as a mixture of naphtha as feedstock for steam-cracking processes to make high value chemicals (ethylene, propylene, aromatics, etc.).

As can be viewed above, the refinery process is of benefit mainly to the transport industry, providing the fuel for most transportation methods.

6.2 Decarbonisation technologies

To provide visibility on decarbonisation options, the report will first study and elaborate on conventional manufacturing methods. This will provide a comparison baseline from which to evaluate other decarbonisation technologies. This baseline is compared with: (i) current Best Available Technologies (BAT); Carbon Capture and Storage (CCS) options; and (iii) novel decarbonisation technologies.

¹⁸⁹ Concawe; 2013; *Oil refining in the EU in 2020; with perspectives to 2030*

¹⁹⁰ IEA; 2013; *Recent developments in EU Refining and Product Supply*; Presentation at EU Refining Forum, 12 April 2013

¹⁹¹ ACEA, 2015

Refineries treat raw petroleum products to deliver the hydrocarbons our modern economy relies upon. These include the gasoline and diesel powering most of our automobiles. They also produce the kerosene for jet fuel. It underpins most of today's modern way of life.

Decarbonisation of the industry can be improved by incorporating best available technologies, as described below. Novel decarbonisation techniques can be split into four main categories:

1. **Process Improvements**, mainly looking at methods to optimise heat usage and recover waste heat for new purposes;
2. **Carbon Capture and Storage systems**, meaning to keep core production as is, but trap released gases from the process, allowing for reduced CO₂ emissions;
3. **Finding an alternative feedstock**, looking to use a biomass source for the raw petroleum feedstock. CO₂ emissions would be reduced as the feedstock would absorb CO₂ during its growth;
4. **Fuel alternatives**, looking to reduce demand for refinery products through new transport options.

Table 6.1 and Table 6.2 below presents the summary of decarbonisation options for the refinery sector.

Table 6.1 Technology readiness levels (TRL) of selected mitigation options in the

Clusters of mitigation options	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	TRL 10
Integrated process improvement / energy efficiency			Waste heat recovery			
Fuel/Feedstock switch		Biocrude				
		Blue fuel synthesis				
CCS and CCU		CCS and Oxy-fuel				
Material efficiency (downstream)						
Material substitution (downstream)						Electric vehicles
					Biofuel vehicles	

Refinery industry

Table 6.2 Main characteristics of selected mitigation options refinery industry

Technology option	TRL	Max. emissions reductions ¹⁹²	Electricity savings ¹⁹³	Energy savings ¹⁹⁴	Market entry	Reference technology
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¹⁹² The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

¹⁹³ Compared to reference technology

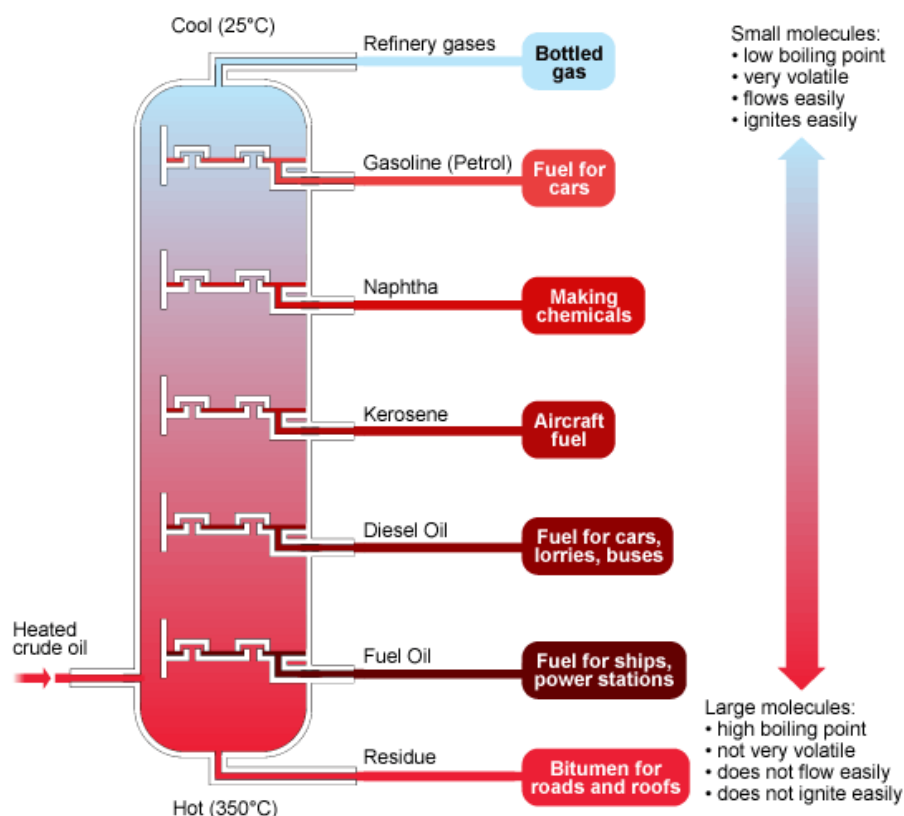
¹⁹⁴ Energy savings show the reduction in energy consumption resulting from the technology change

Technology option	TRL	Max. emissions reductions ¹⁹²	Electricity savings ¹⁹³	Energy savings ¹⁹⁴	Market entry	Reference technology
Waste heat recovery	7	Up to 10%	Reduced waste heat	-10%	Present	Gas heated column
Biocrude	6 - 8	Up to 85%	Sustainable raw material		2025/2030	Gas heated column
Blue fuel synthesis	5 – 7	Up to 100%	Reduced refinery demand		2025/2030	Gas heated column
CCS: post-combustion	6 – 8	Up to 90%			2030+	Gas heated column
CCS: Oxy-fuel	6 – 8	Up to 96%			2025+	Gas heated column
Electric vehicles	10	up to 50%	Reduced refinery demand	-48%	Present	Gas heated column
Biofuels	9 - 10	up to 50%	Reduced refinery demand	-18%	Present	Gas heated column

6.2.1.2 Conventional production methods

In refining, the petroleum (or mineral oil) is heated in a closed environment to high temperatures (circa 400 degrees C). This ensures that the chemicals are heated in a closed environment, void of any oxygen; this is crucial, or the petroleum would ignite. The heated crude oil is then placed at the bottom of a fractional distillation column. At this high temperature, the lightest molecules will rise to the top, enabling the different components of the crude oil to be separated. As the elements rise in the distillation column, they will cool, allowing different elements to condense and be extracted. Steam is also pumped into the column to favour the distillation process. This process is shown in the diagram below.

Figure 6.1 Refinery process schematic¹⁹⁵



Before the refinery process, the crude feed is desalted before heating it in the distillation column. After the compounds are separated, they can be subject to treatments such as further separation, scrubbing (notably through hydrogenation) or cracking. This requires the distillation plant to provide more energy (heat or electric), steam and Hydrogen gas. These all require more energy from gas or electricity. The hydrogen is generally produced through methane reformation, require steam and producing a steady stream of CO₂ along with the H₂. The process is therefore heavily reliant on a source of water and electricity on top of fossil fuel feed.

Approximately 20% of the primary energy used in petroleum refining manufacturing is lost during utility production (encompassing generation, transmission, and distribution), with 9% associated with electricity production and the remaining 11% with steam production.¹⁹⁶ The ratios of the different products are elaborated in the value chain analysis.

The petroleum refining sector is energy and raw material intensive, with energy costs contributing to a significant part of production costs (i.e., energy costs account for 60% of operating costs in refineries)¹⁹⁷.

Together the 96 EU mainstream refineries consume nearly 50 Mtoe total energy per year, which is equivalent to about 7% of their crude oil intake. This means that 93%

¹⁹⁵ <https://www.bbc.com/bitesize/guides/zshvw6f/revision/3>

¹⁹⁶ US Manufacturing Energy Use and Greenhouse Gas emissions Analysis, US Dept of Energy, 2013

¹⁹⁷ DG Ener; 2013; *Summary and conclusions of the first meeting of the EU Refining Forum held on the 12th of April 2013*

of the energy content of the crude oil processed by the refinery is ultimately available in the refined products.¹⁹⁸

One can estimate the emissions to correspond to 240 kg of CO₂ per ton of crude processed.¹⁹⁹

6.2.1.3 Incremental CO₂-reductions with BATs

Between 1992 and 2010, EU refiners have improved energy efficiency by 10%; “low hanging fruits” opportunities have been addressed. Further opportunities are present but are assumed difficult to achieve due to not being cost-effective. Considering this, the total energy requirement of EU refineries is forecasted to decrease from 45 million TOE/annum in 2008 to 39 million TOE/annum in 2030.²⁰⁰

BAT techniques for the refinery sector are split into three major categories:

- **refinery techniques** – upgrading the fractional distillation unit and flaring, where excess gases are burned rather than allowed to be released into the atmosphere (these gases have a much higher greenhouse effect than CO₂).
- **design improvements** – these can be made to optimise the performance of hydrocrackers, fluid catalytic cracking and vacuum distillation unit.
- **upgrading supporting equipment** – lighting, maintenance for fouling control, motors, pumps, compressors and fans.

Considering the current adoption rate and technology applicability, incorporating all these BATs would reduce refinery emissions by 25%, this would equate to a saving of 34.5 million tons of CO₂ eq.²⁰¹

6.2.1.4 Decarbonisation with CCS

Carbon Capture Storage (CCS) is an appropriate solution for the refinery industry. The CCS chain consists of three main stages: (i) Capturing of CO₂; (ii) transportation of CO₂ and (iii) Storing of CO₂ in a secure geological formation. Capturing the CO₂ essentially means to compress the gas into a sealed container. This usually also involves a separation process to extract the CO₂ from the flue gas (if capturing the CO₂ after combustion it would be mixed with air hence N₂, O₂ and water). Separation technologies include cryogenic process, solid or liquid absorption and selective membranes. Transport like any other gas can be done through compressed tanks or pipes. For storage, the carbon dioxide is injected into an underground geological formation (depleted oil or gas reservoirs are good candidates). Once injected, the carbon dioxide moves up through the storage site until it reaches an impermeable layer of rock (which cannot be penetrated by carbon dioxide) which traps it underground.

Ideally this process is useful for large industrial processes, producing lots of CO₂ at high concentration. This saves costs (and energy) for separating the CO₂. Geographical proximity to the storage site of course also a source of savings regarding CO₂ transport.

CCS can be done in three different methods:

¹⁹⁸ EU refinery energy systems and efficiency, Concawe 2012

¹⁹⁹ Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, *Oil Refining*, 2015

²⁰⁰ Concawe; 2013; *Oil refining in the EU in 2020; with perspectives to 2030*

²⁰¹ Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, *Oil Refining*, 2015

- Pre-combustion capture; a process where the fuel (generally methane or coal) is reformed to hydrogen and CO₂, allowing the CO₂ to be stored and the hydrogen to be used as a fuel elsewhere. This process provides a near 100% concentration CO₂ stream.
- Post-combustion capture; is a process where the fuel is burned in a classical fashion, but the resulting fumes are captured. The CO₂ is then extracted from the stream and stored.
- Oxy-fuel combustion system separates oxygen and nitrogen from the air, and feeds only oxygen into the combustion chamber. The resulting gases from combustion are then trapped and stored. This technique has an advantage over the post-combustion capture, as the stream of gas created is much higher concentration of CO₂, and the fuel burns more efficiently.

For the refinery industry, multiple processes are candidates for CCS. The three main carbon producers to target are the CHP plant (which feeds heat to the fractional distillation unit), the methane reformation unit producing hydrogen and the fluidised catalysed cracking unit.

The methane reformation unit is an ideal target for capture as the CO₂ stream produced is at very high concentration. Oxy-fuel combustion can be done for the CHP plant and fluidised catalysed cracking, which would enhance the combustion reaction, and render subsequent capture easier.

A post combustion CCS process is estimated to be able to deliver a 90% saving in CO₂ emissions, and 96% for the oxy-fuel process. These are both already at a TRL level of 7. The cost would be €100-500 per ton of refined product capacity.

6.2.1.5 Decarbonisation with novel techniques

Waste heat and energy recovery technologies

Mitigation potential

The refinery process requires a lot of heat, from the main distillation column, the methane reformation process, steam generation and fluidised catalysed cracking process. Most refinery plants already have a combined heat and power plant for the main distillation column, but the heat can be recovered for all the other process as well, along with the heat generated from auxiliary processes, such as compressors, pumps, etc. This heat can be recovered for low power generation, internal process uses or local community heating. This is estimated to deliver a further 10% carbon savings that can be delivered from these processes. This would equate to 14 million tons of CO₂ eq. of emissions avoided.²⁰²

Costs and TRL

Waste heat and energy recovery are quite well developed, though some new techniques would need to be developed for specific areas of the refinery process. As such it has a TRL of 6-8. The savings are expected to be relatively inexpensive compared to refinery scales, showing less than €50 per ton of refinery capacity.

Application of technology

The technology can be applied to existing processes, though may need to stop plant operation to implement the changes as it could require new pipework being installed. This would need extra maintenance to inspect pipework etc., however, the

²⁰² Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050, *Oil Refining*, 2015

technology doesn't change the need a change of the process inputs and outputs, which means the general product is unaffected. Full exploitation would, however, require outputs for extra heat and power generated. As refinery plants currently already exploit power to the grid, the developments would be needed if heat were exported to local community.

Demand reduction through alternative transport

Mitigation potential

As the main products from the refinery industry are for transportation industry, a major method to reduce emissions is to reduce the demand from the transportation industry. Three main technologies are put forward to this effect: electric vehicles, hydrogen fuel cell vehicles and biofuels.

Electric vehicles are estimated to take up 80% of the EU car fleet by 2050.²⁰³ This would reduce the need for gasoline, the main product from refineries. However, electric vehicles are a good solution for lower power applications, such as commuter vehicles. For heavy goods vehicles, a higher energy density would be required, capable of delivering power for a longer scale. This would ideally be provided by hydrogen Fuel cells or biofuels. Biofuels have the advantage of being capable of synthesizing an artificial diesel, and even possibly a form of kerosene to be used by aviation. Therefore, this estimates a possible reduction in demand for refinery goods of 66%, which would equate to 92.4 million tons of CO₂ eq emissions avoided, if the biofuels and electricity is from a renewable source.

Costs and TRL

The cost in this instance would not be to the refinery industry but rather to the consumer looking to change vehicles and the infrastructure changes required for the electric charging facilities. These technologies are all at high TRL, though Fuel cells and biofuels for transportation are yet to become mainstream in the EU. Biofuels in the aviation industry are still in development, bringing the total TRL from 6-10.

Application of technology

The application of electric vehicles requires a review of the electricity grid, to support the extra peak demand from vehicles and the installation of charging points at frequent locations. The development of fuel cells would require the production and distribution of Hydrogen. The gas can be produced by methane reforming or by electrolysis. If the former, it would need to be produced industrial sites and then shipped to refilling stations. Electrolysis could be performed at a smaller scale allowing for a distributed hydrogen production. Biofuels are easier on infrastructure as the refilling stations would be near to the same of existing petrol stations. However, a concern is raised here with regards to the origin of the biofuel. These concerns are mainly focused on if there is enough land to generate these goods, and if these crops displace food crops, bringing an ethical dimension to the technology.

Biomass hydrothermal liquefaction and biocrude-oil

Mitigation potential

²⁰³ European Energy Agency

Biocrude or biomass hydrothermal liquefaction are processes to create synthetic crude in development as a substitute to petroleum. The oil is created through a pyrolysis process, where organic matter is heated at elevated temperature in the absence of oxygen. This favours the biomass to decompose into base hydrocarbon material which can be used as a refinery feedstock. The “biocrude” created can be processed in a refinery to then create fuels. The production of biocrude requires more energy than petroleum, as the biomass needs treatment into crude, and is of lesser quality (approximately 10% more). However, when counting the energy required for raw material acquisition, transport and combustion at the point of use (negated in biocrude by the absorption of CO₂ during plant growth), the use of biocrude emits 85% less carbon than petroleum.²⁰⁴

Costs and TRL

Currently the costs of production of the biocrude is estimated at 1086 € per ton of bio-jet fuel produced. The technology has been proven but not brought to a commercial level, the TRL is 5-6.

Application of technology

The biocrude can be produced from residual biomass, such as wood chippings or algal growth. These are not competing with food crops and can be grown on land not suitable for food crops. Nonetheless, replacing all refinery feedstock with biocrude would require huge amounts of biomass. An advantage though is that many of the refinery infrastructure could be reused to process this new crude and allow for the diversity of hydrocarbons to be extracted.

Synthetic fuel synthesis

Mitigation potential

The technology combines CO₂ (from atmosphere) and hydrogen to create hydrocarbons. Electricity is provided to enable the reaction. The current efficiency rate is of 70%, where for 1.1 toe of electricity input, 0.7 t of synthetic fuel is produced. However, if the electricity is not provided by renewable sources, the lifecycle footprint of the fuel is three times more than that of fossil diesel.

Costs and TRL

The production of the fuel is heavily tied to the price of electricity. Currently more expensive than fossil fuel, synthetic fuel is still within reach of the consumer. A demonstration plant is already in operation in Dresden, bringing the TRL to 5-6.

Application of technology

The process allows the manufacture of car fuel from CO₂ in the air. This product has no need of refinery activity, bringing energy demand on that front down. If the supplementary electricity required to synthesise the fuel comes from renewable sources, then the total lifecycle of the fuel would be carbon neutral. The synthetic fuel is directly ready for car consumption, being created with no aromatics, no sulphur compounds and at an optimal octane rating for combustion. At this point, however, the technology isn't capable of scaling up to provide large fuel outputs. There would also be a need for the increased electricity generation and cabling to generate all fuel in this manner.²⁰⁵

²⁰⁴ Analysis of biomass hydrothermal liquefaction, *Renewable energy* 113 (2017)

²⁰⁵ DeChema 2017

7 Annex 1: Main decarbonisation technologies

Table 7.1 Main characteristics of selected mitigation options iron/steel sub-sector²⁰⁶

Industrial Sector	Technology option	TRL	Max. emissions reductions ²⁰⁷	Energy savings ²⁰⁸	Market entry	Reference Technology
Iron and steel	Hydrogen based direct reduction (H2-DR)	7	up to 95%	20%	2030 / 2035	BF/BOF steelmaking
Iron and steel	Electrolysis of iron ore	6	up to 95%	40%	2040	BF/BOF steelmaking
Iron and steel	Smelting reduction (without CCS) ²⁰⁹	5-6	up to 35%	20%	2025[e]	BF/BOF steelmaking
Iron and steel	Top gas recycling blast furnace (without CCS) ²¹⁰	7	up to 25%	15%	2025+	Blast furnace
Iron and steel	Carbon capture and usage	5-7	tbd	Tbd	2030+	BF/BOF steelmaking & production of chemicals
Iron and steel	Near net shape casting	8-9	up to 60%	60%	2020+	Conventional hot rolling processes
Chemicals: Ethylene	Catalytic cracking of naphtha	8	Up to 20%	20%	2020	Naphtha steam cracking
Chemicals: Ethylene	Low mechanical quality plastics replacements	6 - 9	Up to 11%	11%	2015	
Chemicals: Ethylene	Plastics recycling	9	Up to 11%	11%	1980s	Naphtha steam cracking
Chemicals: Ethylene	Methanol to ethylene production	8 - 9	Up to 47%	47%		Naphtha steam cracking
Chemicals: Ethylene	Carbon capture and storage furnace	5 - 8	Up to 90%		2030+	Naphtha steam cracking

²⁰⁶ The figures presented here are the expectations these technologies would deliver rather than forecasts. A measure of uncertainty is attached to each, with justification for these expectations written in the report detail for each technology.

²⁰⁷ The maximum emissions reductions possible for the technology are counted whereas 100% being the current emissions from the process and the savings are the reductions if electricity sources to the process are renewable.

²⁰⁸ Energy savings show the reduction in energy consumption resulting from the technology change

²⁰⁹ Higher potentials with CCU/S: up to 80%.

²¹⁰ Higher potentials with CCU/S: up to 60%.

Industrial Sector	Technology option	TRL	Max. emissions reductions ²⁰⁷	Energy savings ²⁰⁸	Market entry	Reference Technology
Chemicals: Ethylene	H2O and CO2 conversion to ethylene	3 - 4	Up to 216% ²¹¹		2030+	Naphtha steam cracking
Chemicals: Ethylene	Selective membrane for organic filtering systems	6 - 7	Up to 10%	5%	2020/2030	Naphtha steam cracking
Chemicals: Ammonia	H2 production through Solid Electrolyte membrane electrolysis	6 - 7	Up to 75%	9%	2025	Methane steam reformation
Chemicals: Ammonia	H2 production through Proton Electrolyte Membrane electrolysis	7 - 8	Up to 75%	8%	2015	Methane steam reformation
Chemicals: Ammonia	H2 production through Alkaline electrolysis	7 - 9	Up to 75%	8%	2020	Methane steam reformation
Chemicals: Ammonia	Carbon capture and storage furnace	6 - 7	Up to 97%		2030+	Methane steam reformation
Non-Metallic minerals: Cement	Low carbon cement (e.g. Aether)	8-9	up to 30%	~15%	<2020	Ordinary Portland Cement
Non-Metallic minerals: Cement	Low carbon cement (e.g. Celitement)	7	up to 50%	30-40%	2020	Ordinary Portland Cement
Non-Metallic minerals: Cement	Low carbon cement (e.g. Solidia)	8-9	up to 70%	~20%	<2020	Ordinary Portland Cement
Non-Metallic minerals: Cement	Recycling of concrete	7			2025+	Ordinary Portland Cement
Non-Metallic minerals: Cement	Carbon reinforced concrete	7-8			2020	Steel reinforced cement
Non-Metallic minerals: glass	CCS furnace	6 – 7	Up to 75%		2030+	Gas furnace
Non-Metallic minerals: glass	electrification	6 – 7	Up to 75%	56%	2020/2030	Gas furnace

²¹¹ This process has a CO2 emission reduction above 100% as CO2 is captured as feedstock to the production process. The feedstock needs surpass the CO2 process emissions.

Industrial Sector	Technology option	TRL	Max. emissions reductions ²⁰⁷	Energy savings ²⁰⁸	Market entry	Reference Technology
Non-Metallic minerals: glass	Oxy-fuel combustion	6 – 8	Up to 46%	20%	2025	Gas furnace
Non-Metallic minerals: glass	Batch preheating	8	Up to 33%	7%	2020	Gas furnace
Non-Metallic minerals: glass	Biomethane	10	Up to 75%		Present	Gas furnace
Non-Metallic minerals: glass	Glass recycling	9	Up to 41%	15%	present	Raw materials preparation and smelting
Pulp and Paper	Black liquor gasification	8-9	up to 10%	15%	<2020	Conventional chemical pulping process
Pulp and Paper	New drying techniques	5-7	up to 20%	10%	2020	Conventional paper mill
Pulp and Paper	Enzymatic pre-treatment	6-8	n.a.	25%	<2025	Conventional mechanical pulping process
Pulp and Paper	Deep eutectic solvent pulping	3	process dependent	40%	2030-2035	Conventional mechanical, chemical pulping process
Pulp and Paper	Flash condensing with steam	3-4	up to 50%	20%	2025-2030	Conventional chemical pulping process
Refineries	Waste heat recovery	7	Up to 10%	10%	Present	Gas heated column
Refineries	Biocrude	6 - 8	Up to 85%		2025/2030	Gas heated column
Refineries	Blue fuel synthesis	5 – 7	Up to 100%		2025/2030	Gas heated column
Refineries	CCS: post-combustion	6 – 8	Up to 90%		2030+	Gas heated column
Refineries	CCS: Oxy-fuel	6 – 8	Up to 96%		2025+	Gas heated column
Refineries	Electric vehicles	10	up to 50%	48%	Present	Gas heated column
Refineries	Biofuels	9 - 10	up to 50%	18%	Present	Gas heated column