RE4INDUSTRY

100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

D3.1 - EIIs Sector Status in Europe – Table of Contents

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	The Netherlands
	Spain

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RE4INDUSTRY

100% Renewable Energies for Energy Intensive Industries

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D3.1 - EIIs Sector Status in Europe – EU Overview

Author: Aimilia Lympeti, Manolis Karampinis

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Abbreviations

Abbreviation	Definition
CO_2	Carbon dioxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
SDGs	Sustainable Development Goals
EII	Energy Intensive Industry
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
RE / RES	Renewable Energy / Renewable Energy Sources

1 Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe. The report is an executive summary of all the sectors reports presenting the most important facts. Its aim is to capture the current status of the European industrial sector, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonization.

Firstly a general overview of the European landscape is presented and then each chapter gives a general overview of the corresponding sector and its importance for the European and global economy. The sectors presented are the non-ferrous, steel, cement, lime, chemicals, fertilizers, ceramics and glass sector. The report provides information on the current usage, the production processes, the energy and GHG emission profile, as well as potential alternatives for mitigating their climate impact. Finally, are discussed the overall challenges and barriers that European industries face and potential measures and solutions for a decarbonized future in Europe.

The report is supplemented with four Annexes, which presents briefly the status of energy intensive industries in RE4Industry partner's countries: Germany, Greece, Netherlands and Spain.



2 General overview

Europe has decided that by 2050 will have succeed to fully decarbonize the industrial European sector fulfilling the ambition for carbon neutrality .Time is short, with 2050 only one investment cycle away, and any further delays will hugely complicate the transition. As the EU ponders its industrial future, this transformation should be a clear priority.

Resource and energy intensive industry holds a central place in this vision. The production of key materials and chemicals –steel, plastics, ammonia and cement – emits some 500 million tons of CO2 per year, 14% of the EU total. Materials needs are still growing, and on the current course, EU emissions from these sectors might increase as well. Globally, these emissions are growing faster still, already accounting for 20% of the total. The EU needs to lead the way in combining the essential industrial base of a modern economy with the deep cuts to emissions required to meet climate targets.

The European industry consists of many different industrial sectors who need electricity and heat for their production processes. During these processes CO2 emissions are produced mainly due to the fuel combustion, due to production of required electricity but also due to process emissions. The process emissions are inevitable and the most effective solution is the use of CCS(U) techniques. Regarding the emissions related to the electricity, one potential measure is the use of electricity produced from RES. Finally the emissions produced from fuel's combustion could be avoided by switching the fuel mix with fuels that are not contributing to the carbon footprint such as the use of biomass. These solutions is a general approach, however each sector has its unique particularities.

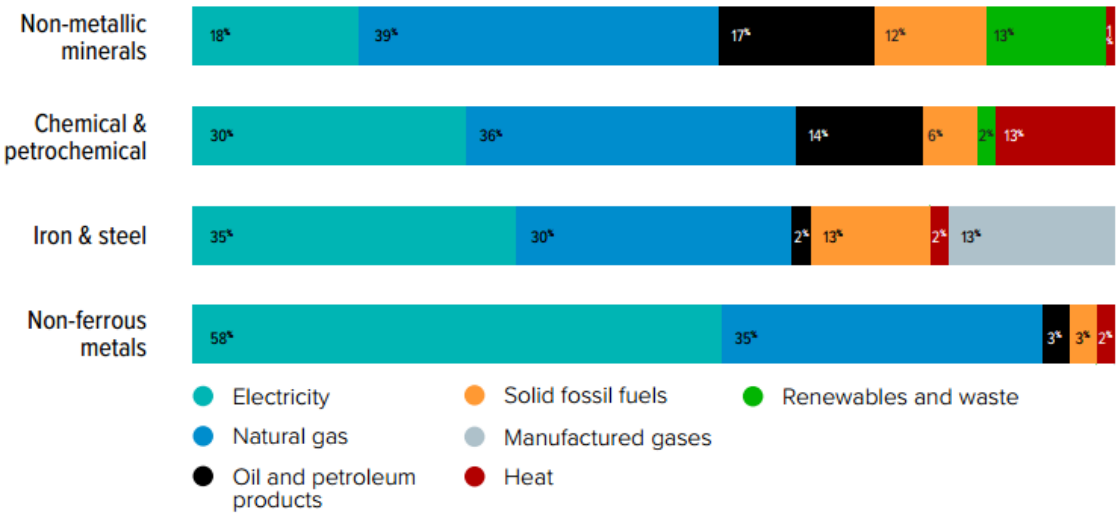


Figure 1 - Relative shares of energy carriers in the final energy use of different EII sectors

The zero-carbon transition of heavy industry is not only feasible but also beneficial for the companies. By embracing more climate friendly practices they can ensure their long-term competitiveness in a world that is inevitably moving towards a climate-safe future. However, many carbon intensive sectors has already been picked when it comes to reducing emissions. New ways of thinking, from circular economy to a technological shift with break-through solutions are necessary to completely transform the way these sectors work and produce.

Such a transformation, however, is costly and risk-intense, and will not take place without smart and committed public policies. Governments' support will be vital to bolster industry innovation: they can reduce the risks and capital costs of low-carbon projects, create markets for new products through public procurement, and they must avoid regulatory misalignment.

3 Non-ferrous metals

Non-ferrous metals are the metals - including alloys – that do not contain iron (ferrite) in appreciable amounts. Generally, they are categorized in four main groups. The base metals, the precious metals, the specialty/technology metals and the rare earth elements/metals. Apart from non-ferrous metals this group also includes silicon and ferroalloys. Silicon is a metalloid which means that has properties intermediate between those of a typical metal and a typical non-metal and it has a significant importance to the economy since it is considered a technology material. It can be considered as a by-product as it is frequently alloyed with non-ferrous metals and its EU production in global share is 9%. Ferroalloys are alloys of iron with a high proportion of one or more other elements such as manganese (Mn), aluminium (Al), nickel (Ni), or silicon (Si).

The wide use of non-ferrous metal relies on the advantages that make them desirable in many applications and they are particularly indispensable and irreplaceable in the production of low-carbon technologies. They include high corrosion resistance, great electrical and thermal conductivity, low density (low weight), and non-magnetic properties.

The non-ferrous metals industry in Europe is worth EUR 120 billion, employing around 500,000 persons directly and more than 2 million people indirectly. The sector consists of 931 facilities, including mining (54 facilities), primary and secondary production of metals (464) and further transformation (413). The EU primary production of non-ferrous base metals in 2016 represented 10% of global metals production in 2016 (13 Mt out of 128 Mt). The EU still has an important share of primary production as a percentage of global production: 4% for aluminium, 13.1% for copper, 9.37% for lead, 9.6% for nickel, and 13.4% for zinc. For cobalt and silicon, the figure stands at 10.23% and 9% respectively.



The interests of the European non-ferrous metals industry are voiced by Eurometaux (www.eurometaux.eu). Currently, the association has 61 members which include non-ferrous metals producers, transformers and recyclers, European metals associations and national metals associations.

The non-ferrous metals industry is the most electrified of all energy-intensive industries, with a 58% share of electricity use in its overall energy consumption. As a result, the non-ferrous metals industry is 5 times more sensitive to higher electricity prices than other manufacturing industries. The EU-ETS has a major impact on the sector, as the indirect carbon costs passes from the power producers to the non-ferrous metal producers affecting the competitiveness and economic sustainability of the latter.

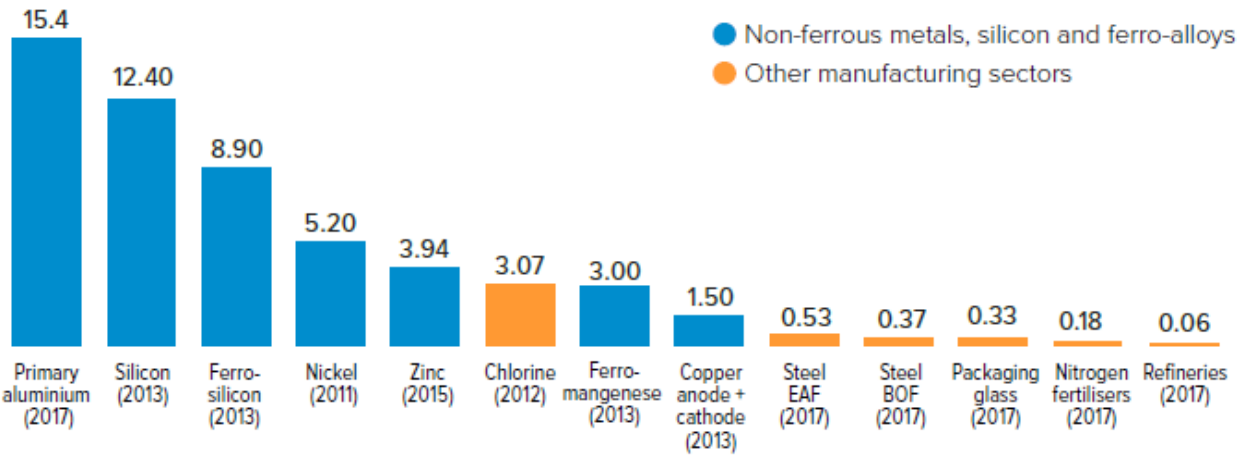


Figure 1 - Average electricity use per tonne metal (MWh/t), (Source: Eurometaux)

Regarding the GHG emissions the EU non-ferrous metal industry had already achieved to reduce its absolute (direct and indirect) emissions by 61% since 1990, the highest reduction achieved worldwide and retaining the potential of reducing the GHG emissions more than 90% until 2050. Such a reduction can be achieved only with the application of decarbonised power there will be a total reduction of 81% since 1990. The remaining emissions could be approached with a wide range of techniques, research, strategy and a supportive policy framework.

Finally a significant characteristic of non-ferrous metals is their ability to be recycled. Since the recycling process is less energy-intensive than extraction and primary production, higher recycling levels will have a very positive impact on the overall carbon footprint of the industry.

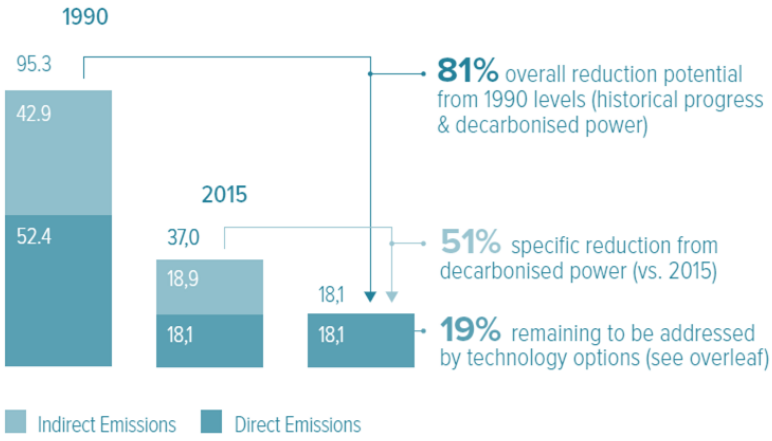


Figure 2- Potential evolution of EU non-ferrous metals industry greenhouse gas emissions from a decarbonised power system, (Source: EEA & Eurostat)

Based on the Figure 1 the most energy/electricity intensive metals were studied. These metals are aluminium, copper, nickel, zinc, silicon & ferroalloys. Non-ferrous metal industry has fully embraced the circular economy since has already achieved high recycling rates and trying to increase them further. The potential solutions regarding their decarbonization are many, however the challenges that the non-ferrous metals is facing are many since the non-ferrous metals industry in Europe is placed in the forefront of the transition to climate neutrality by 2050.

The fact that the non-ferrous metal industry is **highly electro-intensive** means that it has already achieved a remarkable reduction of indirect GHG emissions and therefore a reduction in its carbon footprint, through the increasing decarbonisation and renewable energy uptake in the European power sector is necessary. On the other hand, this points that non-ferrous metals industry is extremely sensitive to **electricity prices,** which affect its economic performance and **competitiveness**. So a **regulatory relief** in electricity pricing is mandatory. **Energy efficiency** is a key element of competitiveness for every energy-intensive industry. Therefore, continuous efforts should still take place in order to explore creative solutions, adapted to local conditions, allowing both improved emissions reduction and energy efficiency. To this direction Europe should invest in innovation but also support the extent use of RES even with the form of **Power Purchase Agreements (PPAs)** The PPAs could be both beneficial for the consumer because this creates a price stability but also for the electricity producer due to the guaranteed revenue stream which will reduce the risks of large investments and hence reduce the cost of capital. Overall, it is beyond doubt that the transition to a decarbonised future will require large upfront capital investments and a central strategic plan for the non-ferrous metal sector

4 Steel

The European iron and steel sector is under pressure due to its CO_2 emissions produced by its high energy and resource intensive processes. In 2018, the European Commission made public its long-term strategy on climate protection to make it a region by 2050 free of the emissions of green-house gases. The sector of conventional steel production in Europe is one of the biggest sources of CO_2 emissions. The sector contributes to approximately 4% of total European CO_2 emissions. Regarding the industrial sector, steel making process in Europe contribute with 22% of CO_2 emissions. Steel in Europe is mainly produced by two routes. The primary route involves the processing of iron ore to produce iron sinter or pellets, and the melting of these in a blast furnace with coke to make pig iron. This is processed in a basic oxygen furnace to create steel. The rest of the steel produced in Europe comes from the secondary route where steel is produced from scrap metal by heating it in an electric arc furnace. While the primary route emits mainly direct greenhouse gases, the secondary route emits mainly indirect greenhouse gases, which depend on the electricity mix used in the electric arc furnace. In consequence, the primary route is the main target to reduce emissions in the sector. In 2020, the steel sector in Europe reported that the industry supported more than 2.6 million total full time equivalent jobs. Crude steel production for 2020 was 139 million tonnes. The Gross Value Added of the European steel industry was €132 billion if direct, indirect and induced effects are factored. The EU sector consumed around 0.84 EJ of energy in 2020. Decarbonisation options are available for both EU routes of steel production. The primary route as the highest CO_2 emitter, is the main target to lower emissions. Methods such as coke dry quenching and optimizing pellet ratios, as well as blast furnace equipment like top gas recovery turbines, reduce conventional primary route carbon emissions. Replacing coke with biomass and natural gas with hydrogen can also significantly cut CO_2 in primary steelmaking, as can inject hydrogen or ammonia into the blast furnace to partly replace pulverized coal. These technologies will still require development in the following years. Lower secondary route emissions can be achieved by making savings on the electricity used to power the electric arc furnace, or shifting the electricity mix towards renewables. Many of the proposed solutions will require massive amounts of affordable green electricity – for iron ore pre-processing, H2 electrolysers, furnaces and electrolysis – to meet the carbon neutrality goal. But such energy sources are far from meeting the required price points compared to coke (excl. carbon tax) and will take time to develop.

5 Cement

Cement is used to make concrete, the most consumed manufactured substance on the planet. Whilst



everyone knows the word cement, it is often confused with concrete or mortar. Cement is a key ingredient in both concrete and mortar, and it is always mixed with other materials before use.In particular cement is a glue which acts as a hydraulic binder, i.e. it hardens when water is added. It is primarily used to bind fine sand and coarse aggregates together in concrete. So if cement is mixed with water, sand and gravel forms concrete, which is what the vast majority of cement is used for and if cement is mixed with water, lime and sand forms mortar. Concrete's remarkable properties make it a vital element and are the reasons that made cement so widespread and make it vital to building a climate neutral Europe.

According to Eurostat data, the cement manufacturing industry in the EU represented an estimated €15.2 billion turnover and €4.8 billion in value added. Germany, France, Italy, Spain, Poland and Belgium together accounted for 71% of EU's turnover, 70% of EU's enterprises and 68% of EU's employment in the cement sector. In 2019, the sector offered employment to more than 47,000 [1] persons in Europe, distributed over around 350 enterprises.

The interests of the European cement industry are voiced by Cembureau (https://cembureau.eu/) which is the representative organisation of the cement industry in Europe.

Cement is obtained by grinding cement clinker and, in some cases, supplementing it with additions. Clinker is produced through the firing/sintering (in a cement kiln) of a mixture of limestone (or other minerals containing high levels of calcium) and other materials (e.g. clay, shale, sand, iron ore, bauxite, fly ash and slag) to provide the necessary final chemical composition. A typical-ly cement (Portland) clinker mix would contain approximately 80% limestone and 20% clay. Clinker is a nodular material before it is ground up, nodules can be anything from 1mm to 25mm or more in diameter. Concrete is a mixture of cement, water and aggregates and in some cases a small amount of ingredients called admixtures. Aggregates make up approximately 60-75% of the mixture and cement and water make up the rest.

Cement production involves multiple stages and actors from the quarry to the final product. Cement production is a three-stage process: raw materials preparation, clinker production and clinker grinding with other components to produce cement. Different raw materials are mixed and milled into a homogeneous powder, from which clinker is produced in high-temperature kilns where direct emissions of CO_2 occur. Clinker is then intergrounded with gypsum to produce cement. Other components, including fly ash, ground granulated blast furnace slag (GGBFS) and fine limestone, can be interground or blended, depending on the required technical properties of the finished cement.

Every stage of the cement manufacturing process requires energy. Almost 50-60% of the total production cost is linked to the energy costs, which explains why cement industry is considered an



energy intensive industry. Thermal energy accounts for about 20–25% of the cement production cost and the electrical energy represented 13% of total energy use and 6% of total CO_2 emissions related to cement manufacturing according to Cembureau. The typical electrical energy consumption of a modern cement plant is about 110–120kWh per ton of cement and requires 60 to 130 Kg of fuel oil or its equivalent, depending on the cement type. Primary energy consumption in a typical cement plant is up to 75% fossil fuel and up to 25% electrical energy (dry process).

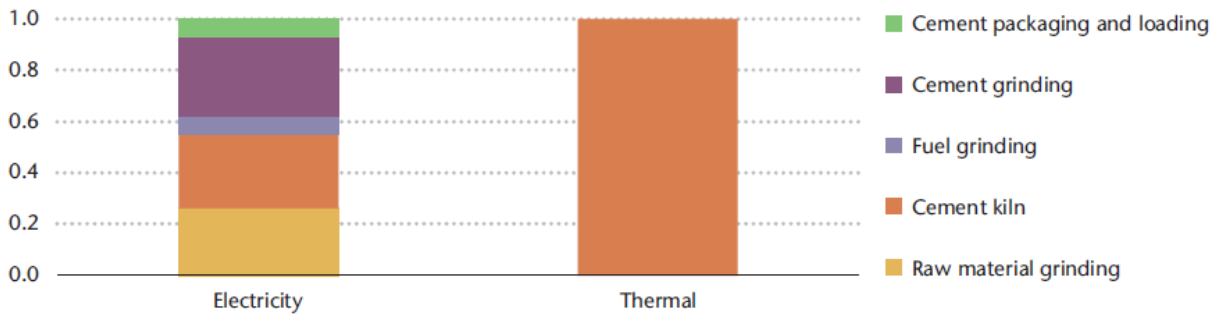


Figure 3 - Energy demand distribution by process step

Regarding the CO_2 emissions, cement production is responsible for 5% of total EU CO_2 emissions. The cement industry is an energy-consuming industry in which carbonate (CaCO3) decomposition releases a large amount of CO_2 and produces 0.6 tonnes of CO_2 when producing a tonne of cement.Thus, the clinker production process generates direct CO_2 emissions due to fuel combustion and the carbon released from raw materials makes cement manufacturing is a CO_2 intensive process. The process emissions account for around 60% of total CO_2 emissions. The remaining 40% of CO_2 emissions arise from direct and indirect energy emissions, i.e. the combustion of fuels required to generate the necessary heat (direct emissions) and any emissions from electricity generation (indirect emissions). However, it is important to note that concrete also acts as a carbon sink over its lifetime as it absorbs and stores CO_2 emitted in the production of its ingredients.

The European cement industry has actively worked on reducing emissions for a long time. Since 1990, **it has reduced its CO_2 relative emissions by about 15%.**Over time it will be possible to significantly reduce the energy emissions in cement manufacturing through **fuel substitution** with other sources of energy. Moreover the use of **electrical heating, plasma or solar energy** to calcine the raw materials could result in the future in saving 55% of the fuel CO2 if renewable electricity is used. Combined with the use of **hydrogen and biomass fuels** for the clinker process, this could result in near zero fuel CO2 emissions. Reduction of process emissions needs significant technological innovation, both in the manufacturing to reduce their release with the use of alternative decarbonated raw materials for instance, and through **carbon capture technology**. Some other measures that can be taken to reduce the emissions is the use of **new types of cement clinkers**

which are chemically different from conventional Portland cement clinker and result in 20 – 30% CO_2 savings by reducing the amount of limestone in the formulation and because they require less energy. Moreover, the **ration of clinker in cement** could be another alternative measure. Action is already being taken in both these areas, but more work is required, and the industry is already investing heavily **in research and innovations** to reduce these emissions.

Towards this direction, it is of crucial importance to act rapidly and to create the **right regulatory and financial framework.** For supporting the research and development of breakthrough technologies as well as the acceleration and scaling-up of proven efficient low carbon technologies, with a particular focus on CCUS and new and alternative binders, policies should help mitigate the risk through investment mechanisms that allows investments against reasonable returns. Moreover energy intensive industries, including cement, will need sufficient i**nfrastructure to transport, re-use and store the CO_2 captured.** The EU should urgently look at developing a pan-European CO_2 transportation network that responds to the industry's needs. Another aspect which is really important to all energy intensive industries and cement industry as one of them is **the price of renewable energy and in general the electricity price**. In order to boost the supply, distribution, availability and affordability of renewable energy it needs to make renewable energy affordable for industry. Finally, governments should pursue efforts towards developing **stable and effective international carbon pricing mechanisms** to ensure local lower-carbon cement production remains competitive against higher-carbon cement imports.

6 Lime

Calcium carbonate (CaCO3), is a raw material that is widespread and comprises more than 4% of the earth's crust. The feedstock for lime production is calcium carbonate and/or calcium magnesium carbonate. Calcium carbonate is used to produce lime and calcium magnesium carbonate is used to produce dolime respectively. Calcium carbonate can be found in chalk, limestone and marble whereas dolomitic calcium carbonate can only be found in dolomite.

The interests of the European lime industry are voiced by European Lime Association (EuLA, https://www.eula.eu/). Currently, the association is representing 21 national organisations, and approximately 50 companies. The European lime industry employed around 11,000 people directly and produces circa 23 Mt of lime and dolime.

Today, lime is used in a wide range of applications and is necessary to many other sectors like constriction, chemical industry, iron and steel industry and agriculture. Furthermore its properties facilitate other industries to reduce their carbon footprint.



The total world production in 2020 was 420,000t and around 6% of them was the EU production, with Germany, Italy, Poland and France being the largest producers of lime. Regarding the size of industries, the most lime industries in EU are categorized as small to medium size companies and in 2020 there were operating almost 170 plants.

Lime is forming through a calcination process, a thermal decomposition process where limestone (CaCo3) or dolomite $CaMg(CO_3)_2$ under the influence of high temperatures, release carbon dioxide and are converted into lime (CaO) and dolime ($CaMgO_2$). This lime production leads, due to the process itself but also due to heat requirements, to emissions of greenhouse gases. The calcination process is responsible for the most part of energy use and the CO_2 emissions, since the production of lime requires temperatures around 1200^oC and maintaining these temperatures requires a significant amount of heat. Simultaneously, the 68% of total emissions are an inevitable by-product of the calcination process.

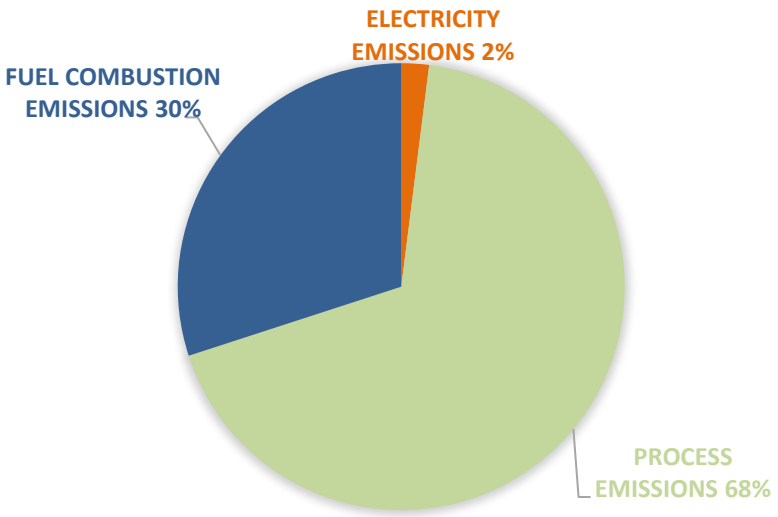


Figure 4 - Average share of CO2 emissions in the manufacturing of lime (data of 2010 (EuLA, 2012)).

In 2010, the average fuel consumption was 4.25 GJ/ton of quicklime with the theoretical minimum energy required to be 3.18 GJ/t lime and the CO_2 emissions reaching 0.751 t CO_2/ t lime and 0.807 t CO_2 / t dolime. The total direct CO_2 emissions of the European lime industry, based on EUTL, the EU-ETS emissions registry, are around 26 Mt CO_2. Regarding the energy use, the production of lime requires heat and electricity, however the electricity consumption is quite low since electricity is mainly used for operating some of the kiln equipment and mechanically crushing the limestone. Electricity consumption is estimated at ±60 kWh/t.

The energy efficiency that is succeed is mainly through the transition to vertical kilns, which are more efficient, since the kiln type plays an important role on the energy consumption. However apart from

the kiln type, desired lime, grain size, humidity of the limestone, fuel quality and residual CO_2 content are some other factors that affects the energy efficiency of the production process.

This energy required for heat comes either from fossil fuels (natural gas, fossil solid fuels and oil) or from waste and biomass, however **lime production has limited flexibility in use of alternative fuels**, due to the impact of energy sources on the purity and cleanness of final products

For the emissions that originate from energy production, the lime industry can apply measures like fuel switch and energy efficiency and as far as for the rest of the emissions which are the 68% of total emissions the only potential solution is the **carbon capture**. As far as concerns the energy efficiency, **switching the horizontal to vertical kilns and in particular to PFRK** is the most efficient method to succeed energy efficiency but also the use of **heat exchangers** in the existing horizontal kilns and energy heat **recovery from the waste heat from the kilns** could also be an option. Switching of fuels, wood powder firing and **biomass** gasification, methanol, turpentine and tall oil may also be available for burning in lime kilns, with **hydrogen** being the most promising option. Regarding the emissions related to electricity use, although the amounts are small (2% of total CO_2 emissions), some measures for greening-decarbonizing the electricity production could be taken, such as the efficiency of **motor systems** and the **optimization of the cooling system**. Finally, through the carbonization which is the reverse reaction of lime production around 2% of CO_2 emissions that produced are captured from the atmosphere forming limestone and by this way the cycle of lime is closing.

The challenges that the lime industry is facing are mainly **financial challenges** due to high carbon costs. These **high carbon costs** have as a consequence high lime prices which leads to reduced EU demand and as a result some industrial sectors relocate their production outside Europe in order to avoid these costs, reducing eventually the competitiveness of the EU lime industry. However, even if the EU industry is trying to overcome these obstacles and reduce the CO2 emissions by investing, a wide scale implementation is currently inhibited due **to high investment costs** but also due to the long payback periods. Accordingly, **CCS-CCU** which is the most important option of lime industry to eliminate the CO_2 emissions, needs to be developed and deployed. **Supporting** this solution, European Commission should consider investigating the possibility of providing **public infrastructure for transporting and storing CO_2.** This enables EU lime industry to quickly take CCS/CCU on board once economically viable.

7 Chemicals

The International Council of Chemical Associations (ICCA) estimates that over 95% of all



manufactured goods rely on some form of industrial chemical process. This explains why in EU industrial scape, the chemical manufacturing is the fourth largest industry in the EU, accounting for 7.6% of EU manufacturing turnover. It consists of 30,000 companies, 95% of which are small and medium size enterprises, directly employing approximately 1.2 million people and 3.6 million indirectly. EU turnover was €565 billion in 2017, where Germany and France are the two largest chemicals producers in Europe, followed by Italy and the Netherlands.

The interests of the European chemical industry are voiced by Cefic (https://cefic.org/) which is the representative organisation of the chemical industry in Europe. Currently is representing 650 members and affiliates.

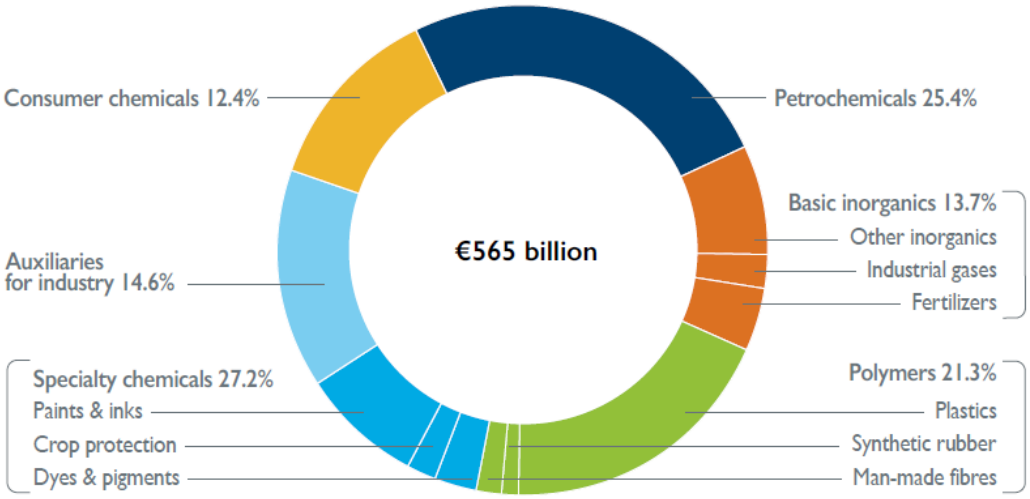


Figure 5 -EU chemical sales 2018 [1]

The most of the EU chemicals are sold to downstream users, which are other industrial sectors [2] . Some of these industrial customers are the rubber & plastics industry, textiles industry, construction, computer production industry and pulp & paper sector. It is therefore evident that chemicals have a wide range of applications that further facilitate the transition to carbon neutrality and support sustainability.

Energy use in the sector is characterized by the use of natural gas to generate steam or for direct heating, and the use of electricity for a range of activities such as for pumping, compression, chilling, and lighting. The combustion of fossil fuel, indirect emissions from electricity consumption, and process emissions (resulting from processes that create CO_2 as a by-product of chemical reactions) make up the chemicals sector carbon footprint. In 2017, the fuel and power consumption of the EU chemical industry, including pharmaceuticals, amounted to 52.7 million tons of oil equivalent and gas with electricity account for nearly two thirds of total energy consumption while energy consumption in chemicals accounted for 20.2% of total industry energy consumption in 2017[3].

The chemical I industry made many efforts to improve energy efficiency and reduce fuel and power consumption. These measurements has led to a reduction of 24% in fuel and power consumption compared to 1990 but also to a reduction of 55% in energy intensity compared to 1991 and characterizing EU chemical sector a pioneer in energy efficiency.

Regarding the **GHG emissions** the EU chemical industry, including pharmaceuticals, emitted a total of 135.2 million tons CO_2 equivalent in 2017. The most important pollutant which is CO_2 was partially restricted however, much of the decline is linked to abatement of nitrous oxide (N_2O) which is the second most important pollutant. However, extra measurements should be taken to reduce further the CO_2 emissions.

The energy-intensive nature of many chemical processes is justified by the high temperatures required for the processes. A range of technologies are used to deliver heat to chemical processes. The most widespread is the use of steam at a variety of different pressures. Steam is generated in boilers which are fired by natural gas or other fuels, or by heat recovery techniques. These techniques include heat removal from exothermic processes (those that generate heat as a by-product), heat recovery from waste streams, or heat exchange where a feedstock stream is pre-heated by cooling a product stream. Furnaces are also used to provide heat directly in some processes where very high temperatures are required, for example in the cracking stage of olefin production. Furnaces provide direct radiant heat compared to conduction of heat through a vessel or tube wall where steam heating is used. Natural gas or recovered waste gases are typically used as furnace fuels, although other fuels can also be used. Where the relative demand for heat and electricity is appropriate, many chemical plants improve their overall energy efficiency by using combined heat and power (CHP). CHP units may be physically integrated with the site, or located on a neighboring site. This is typically done using a natural gas fuel in a gas turbine to generate electricity, followed by a heat recovery steam generator. Alternatively, a steam boiler is used to raise steam to both provide heat and generate electricity via a steam turbine. CHPs often also make use of fuel or waste heat provided by the chemical process [4].

The most important chemicals that are considered as building blocks of chemical industry are **methanol, ethylene, chlorine and ammonia**. Their importance is based on their large production volumes but also their energy and carbon intensity, a combination that is responsible for the most of CO_2 emissions of the chemical sector.

Deep emissions reduction in Europe is technically possible through power supply decarbonisation and CCS integration with chemical processes in the 2030–2050 timeframe [5]. A range of current and future technologies can sustain Europe's track record of energy and emissions intensity



improvements: final energy demand can be maintained at a constant level, and emissions could be virtually eliminated with energy efficiency (33% of the total emissions reductions), CO_2 capture and storage (CCS) (25%), renewable electricity (20%) and fuel switching and measures to reduce nitrous oxide emissions (22%). To enable continuous and competitive production, access to large amounts of affordable and reliable energy and feedstock will be necessary, which can be challenging for renewables [6]. Infrastructure will be crucial, including transmission grids for renewable power, pipelines for hydrogen, CO_2 and heat, and waste logistics and recycling. Key option will be electrification of processes and new catalytic conversion with biomass and recycling being key strategies to reduce fossil feedstock use. For energy supply, clean hydrogen, heat pumps and waste energy use, as well as energy management systems, are low-carbon options for decarbonisation.

The challenges, as an energy intensive industry, chemicals are dependent on climate change and energy policies, therefore, EU chemicals industry is under severe competitive pressure. It faces challenges that include increased international competition, rising energy and feedstock prices, pressure to increase resource efficiency, new regulations, and the need for innovation. In order to remain competitive and become carbon neutral all the above should be discussed and adequate measures should be taken. Toward this direction a **global carbon framework should be developed** to avoid market distortions and minimize carbon leakage, the extended energy efficiency should also be supported and the choice of **feedstock**, such as the use of bio-feedstock or the access to biomass must of be a high importance issue. Moreover, policies should support the development of new technologies and practices that promote more **efficient and sustainable disposal, recovery and recycling options** because the best options to reduce global GHG reductions will involve a **full life cycle approach** to ensure that each stage of the value chain will provide its optimum contribution. Finally despite the current economic situation, governments / policies should continue funding **research and development** focusing on scale, cost, and implementation speed but also could **reward** those companies that are most advanced in implementing CO_2 reduction measures and simultaneously use effective measures to accelerate action in those companies and regions that have fallen behind, always establishing practically **achievable emission targets**.

8 Fertilizers

Mineral fertilizers enables almost half of the global population to be fed so the fertilizer industry can be considered as one of the oldest and large scale chemical industries. Each year, the European fertilizer industry transforms millions of tons of air, natural gas and mined ores into products based on the three essential plant nutrients nitrogen, phosphorus and potassium with ammonia being the



building block of most fertilizers. The European fertilizer industry has more than 120 production sites scattered throughout majority of European Countries. The EU production of fertilizers is relatively small with the total production to be reaching 16.8 Mt in 2019. From this amount the nitrogen represent the 73%, the phosphate the 12% and the potassium accordingly the 16%.

Around half of the fertilizers used are applied on cereals (26% on wheat, 25% on coarse grains), 16% on grassland and 10% on oilseeds. The total volume of fertilizers applied on specialised crops (potatoes, sugar beet, and permanent crops) is relatively low – 11%.

The interests of the European fertilizer industry are voiced by Fertilizers Europe (www.fertilizerseurope.com/). Currently, the association is representing 17 corporate members and 7 national organisations. It employs 74,000 people (including supply chain) and has a turnover of € 9.5 BN.

Three to five per cent of the global annual natural gas consumption is used by the industry to produce N fertilizers. The cost for natural gas represents 60-80 % of the variable input costs for production of N fertilizer. The production of rock-based such P and K fertilizers into a product that can be used by farmers is less energy demanding compared to producing nitrogen and the dependence of natural gas is therefore lower.

Ammonia production is carried out in two stages, the Steam Methane Reforming (SMR) stage for the production of hydrogen, which is the feed material of hydrogen production and the Haber-Bosch stage where hydrogen produced and nitrogen react, producing ammonia. SMR is the main process that is used in Europe since it is the most efficient and economically available technique of hydrogen production at this time.



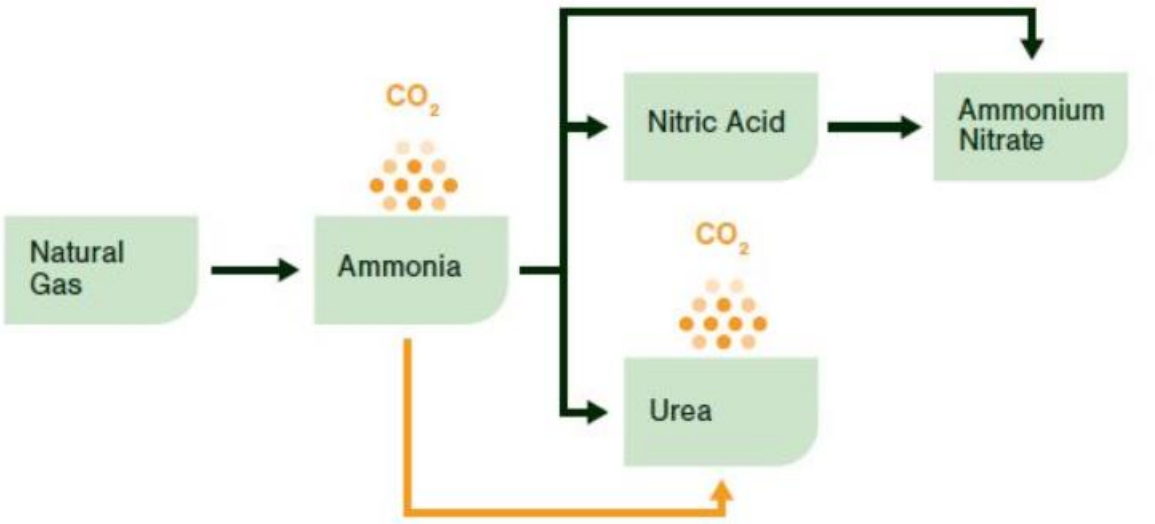


Figure 6 - Current ammonia production process. Source: Fertilizers Europe

Taking into to account that almost the 75 % of the total European production fertilizers production is N fertilizers and that production of ammonia is responsible for the 30 Mt of the total 35 Mt of greenhouse emissions that produced the fertilizer industry in 2020, it is obvious that ammonia is the dominant emitter. The GHG emissions produced along the fertilizers production value chain are mainly due to the combustion of fossil-based energy sources but also CO_2 and CH_4 are emitting from feedstock mining (natural gas), fossil-based electricity heat consumption and the steam reforming process. Approximately 65% of the natural gas is used as the raw material for sourcing hydrogen, with the remainder employed to power the production process. The hard-to-capture CO_2 emissions from the reformer unit in the SMR process usually contribute the most to GHG emissions, followed by CO_2 from the combustion of fuel for steam generation.

As mentioned before, production of nitrogen fertilizers is based on high temperature 'cracking' of natural gas which is the raw material into hydrogen and CO_2. Hydrogen is then combined with nitrogen from the air to create ammonia. Ammonia then, through some other process produces a range of fertilizers such as urea whose production also requires large amounts of energy.

The average energy efficiency for European fertilizers production plants is higher than the global average due to the use of relatively modern technology and reduced use of coal as main energy supply. On average, 1.9 t of CO_2 are released on-site during the production of one ton of ammonia during the conventional method. So, ammonia's production is an emissions and energy-intensive process, relying on fossil fuels, mainly natural gas with the global ammonia production accounts today for around 2% (8.6 EJ) of total final energy consumption.

Due to all the above facts the fertilizer industry is focusing on the decarbonization of ammonia

production which is the main contributor to energy consumption and CO_2 emissions. The potential solutions are categorized in two main options. The first one focuses on the **reduction of the CO_2** emissions and the second one has as goal the **CO_2 avoidance**. The first low-carbon alternative involves the **underground storage of the CO_2 (CCS)** that is generated during the production process of ammonia. The second alternative solution is focusing on alternative sources of H_2 for the Haber-Bosch process. The **electrolysis of water** (yellow and green hydrogen) and **methane pyrolysis** (turquoise hydrogen) are the basic potentials for the decarbonization of fertilizer industry. Finally, hydrogen can be obtained from **biomass**. The main thermochemical processes for the hydrogen production are gasification, pyrolysis and combustion. The disadvantages of this option are that the hydrogen content in biomass is low and the technologies are still immature.

By 2050, under the right conditions, ammonia production could be based on decarbonised sources of energy, using alternative sources of hydrogen and electrolysis based on renewable energy. This way ammonia produced with zero or near-zero carbon footprint could also help decarbonize other sectors, like energy and transport. Due to its high energy density and ease of storage and transport, ammonia is a technologically superior and more energy efficient carrier of hydrogen than hydrogen itself.

Finally, although Fertilizer industry has made tremendous improvements towards its decarbonisation, the challenges and barriers are many, so effective measures are required in order to remain competitive. The most important challenges are the consequences of the EU ETS which affect the EU competitiveness and expose the industry to the risk of **carbon leakage** but also the **cost of producing ammonia** through greener technologies which is currently two to four times more expensive than conventional ammonia making these technologies economically unviable.

According to Fertilizers Europe, a combination of policy solutions is needed to enable the transition to a climate-neutral economy by 2050 while keeping fertilizer industry competitive. The main targets should be:

- Low-carbon and competitively priced energy and feedstock
- Infrastructure to transport low-carbon resources
- Infrastructure for CO_2 management and avoidance
- Funds to finance the transition

9 Ceramic

The EU ceramics industry is a world leader in producing uniquely designed high quality cramic products such as tiles, bricks, sanitary ware, or vitreous clay pipes. Most manufacturers are innovative small and medium-sized enterprises (SMEs). Even though the industry was hit hard by the economic crisis, there are signs of recovery. The ceramics sector provides over 338 thousand jobs and accounts for €27.8 billion in production value. EU manufacturers are mainly represented by SMEs that react quickly to changing demand and new opportunities. The use of automation and environmental technologies are widespread. Clusters fuel innovation and enhance competitiveness. Access to raw materials is of key importance, especially for the refractories sub sector where certain countries control up to 90% of the raw materials (magnesia, bauxite). Ceramics production processes are energy intensive with the bricks and roof tiles sector being the biggest energy consumers. The industry has halved its energy consumption over the last 25 years as a result of a switch in fuel usage. Dust and gaseous emissions arise during the firing or spray drying of ceramics and may be derived from the raw materials and/or the fuels used. Heavy metals can be emitted due to substances used in decoration or the use of heavy oil. Some of the waste from the production process can be recycled back to the kiln. The rest is sent for external recycling (road construction) or disposal (landfill). Some producers are beginning to bring in waste for recycling. Overall, natural gas is the main energy source in kiln. In the process of firing and drying, natural gas consumption reaches approximately 85% of the whole of energy consumption in the manufacturing process. Electrical energy is used mainly for comminution, mixing and forming. It stands for approximately 15% of the energy consumption in the sector. According to the EU Emissions Trading System, total emissions from the EU ceramics sector amount to 19 million tonnes of CO_2 annually. Emissions can be broken down into three main categories: a) Fuel combustion for drying and heating process; b) Process emissions generated by mineralogical transformation of the clay; and c) Indirect emissions, mainly from electricity production. The transition to a competitive low-carbon and resource-efficient economy in 2050 represents a challenging target for the EU ceramic industry. The 2050 emissions reduction targets are even more challenging for a capital-intensive sector with long investment cycles like ceramics. The EU ceramic sector has reduced its total emissions by around 33% since 1990. In the 2000s, by 45%. This has been possible by optimising processes, making production more efficient and by fuel substitution from solid fuel (mainly coal) to natural gas. To achieve carbon neutrality by 2050, the ceramics industry will nearly need 50k TJ each of green hydrogen, biogas, and green electricity. These amounts are not currently available to the industry. Their supply does not exclusively depend on the industry but on many factors, such as infrastructure and the right legal and policy framework. Annual decarbonisation cost of the EU sector will exceed €500 million by



2030. The annual costs will progressively grow to nearly 1 bn EUR per year in 2040 and will exceed 1.2 bn per year in 2050. The total accumulated costs until 2050 are estimated at around 27 bn EUR. Energy efficiency improvements have been made in the EU ceramic sector, resulting in more efficient kiln designs and drying techniques. The drying and firing process has become a continuous process (creating a stable energy demand). However, further decarbonisation is required to achieve net zero (fuel) CO_2 emissions. Relevant categories for further decarbonisation are fuel substitutions, process design, use of residual energy and CO_2 capture and storage (or utilisation).

10 Glass

Glass still represents one of the largest used materials in manufacturing, building and consuming processes, significantly enabling light-weighting products and superior quality glazing. But moreover, glass also represents a 100% recyclable material which contributes to a sustainable society that meets green principles of circular economy. Main findings highlight the use of high-temperature melting furnaces as various heat-intensive equipment for processing stages. This technology within the sector accounts to 1% of total industrial energy share. Most furnaces are fed with natural gas or with fuel oil as standby fuel. Container glass is the largest sub-sector of the EU glass industry. It accounts to around 62% of European glass production (packaging products as bottles and jars for different sectors). Flat glass represents the second largest glass sub-sector of EU glass industries. It accounts for nearly 29% of total EU glass production (residential, automotive, and commercial construction are the main final markets. Flat glass has also innovative applications. Specially for renewable energies and sustainability markets as in solar energy photovoltaic and solar thermal panels or for urban / domestic furniture and greenhouses. Glass manufacturing sectors are considered an EII. Moreover, due to their share and interlinkage with a variety of other main industrial sectors, glass has an economic and strategic importance in EU. The glass sector is undoubtedly an energy-intensive sector. Energy represents one of the largest operational costs in glassmaking. However, it is still hard to find clear and recent data from energy consumptions and emissions of the EU glass industry, as there exist no evident available sources of public data. A switch to biomethane is technically possible, particularly with biomethane of similar quality to natural gas. However, leaving aside the cost, quality requirement and distribution challenges, this potential is directly limited by the quantities available. An average float plant of 650 tonne a day has energy needs slightly above 1.4 million GJ. It results from the above that, even if the current annual production of biomethane, i.e. 19352 GWh equivalent to 70 million GJ25, was to be entirely directed toward the flat glass sector's plants, this would be insufficient to meet the energy needs of today's 52 EU-based float lines. The



injection of more than 20% of green hydrogen in the gas grid would require research to adapt the furnace technology. Hydrogen has a high combustion velocity and a non-luminous flame which makes it difficult to monitor. While heat transfer contributes to the efficiency of flat glass making, hydrogen flames provide relatively low radiation heat transfer. In addition, handling and storing hydrogen on site present difficulties due to its explosive properties. Provided carbon-neutral electricity is available, a major breakthrough in technologies would be needed to make possible full electric melting in glass furnaces. Electric melting is not yet compatible with high temperature glass furnaces with a production above 200 tonnes a day (i.e. 3 times below an average float glass plant). An additional technical challenge to electric melting is that it is not suitable for high cullet ratios as it is difficult to keep down the superstructure temperatures. Therefore, savings from a switch to carbon neutral electricity could partly be reduced by an increase in process emissions.

Annex

Germany

Despite having by far the largest proportion of industrial production in the European Union (EU), Germany's industrial sector has a lower energy intensity than the European average. The target industries of RE4Industry given place below.

Non-ferrous metals: They are divided into light metals (aluminium and magnesium), nonferrous metals (copper, zinc, lead, nickel, and tin), and rare and precious metals. Different stages of industrial processes include raw metal, semi-finished products (strips, sheets, rods, profiles, pipes, and wires), further processing, casting, and hot galvanizing. The German nonferrous metals industry was heavily affected by the COVID19 crisis. The only subsector that was not touched by the crisis is the hot galvanizing sector, which saw a slight increase. The nonferrous metals industry still heavily depends on fossil fuels, and aluminium-related activities are the most polluting ones. Installations in the non-ferrous metals industry emitted around 2.5 million CO_2 equivalents in Germany as of 2020.The sustainability efforts in nonferrous metals are seen through the resource efficiency ensured by recycling. The recycling rates of nonferrous metals are the highest at an international level. A problem within the sector is the migrating production sites to countries with fewer environmental regulations. Therefore, close cooperation between industry and policymakers is necessary to be able to maintain the right balance.

Lime: Lime is a crucial raw material at the beginning of many value chains. The application of lime products varies from environmental production, steel industry, construction industry, and chemical industry to agriculture, forestry, and fish farming. More than 6.3 Mt of CO_2 is emitted by the German



lime industry per year. Even though the more efficient kilns are used within the industry, emissions stayed mainly unchanged due to the use of more pulverized lignite as a fuel. The German Lime Industry (BVK) plans to use Carbon Direct Avoidance, Smart Carbon separation, and Smart Carbon Capture in order to achieve its climate-neutral production goals by 2050.

Cement: The German cement industry is responsible for 2 % of the national total CO_2 emissions. CO_2 emissions from the cement sector are both raw material and energy related. Raw material-related emissions are produced during the limestone decarbonization and account for a slightly more significant portion of the CO_2 emissions than the energy-related emissions. German cement manufacturers have managed to decrease their CO_2 emissions by 20-25% since 1990. Improvements in the thermal efficiency, reduction in the clinker content in cement, and reduction of fossil fuels have been crucial to achieving success in this sector. German cement industry has the highest share of alternative fuels in comparison to cement industries of other EU Member states. Overall, decarbonization of the cement sector is not possible with the conventional methods since process emissions exist. Therefore, the sector heavily relies on alternative technologies like Carbon Capture, Utilisation, and Storage (CCUS).

Chemicals & Fertilizers: The chemical industry is the third-largest industrial sector in Germany, and Germany has the fourth-biggest chemical industry worldwide in terms of revenue. Around 16.9 million tonnes of CO_2 equivalents were emitted by the German chemical industry only in 2020. Production of bulk materials is the activity that causes the most emissions, followed by ammonia production. The German Chemical Industry Association (VCI) developed three paths to greenhouse gas neutrality that will be achieved through the reference pathway, the technology pathway, and the GHG-neutrality pathway. The roadmap VCI developed shows that the greenhouse gas neutrality of the German chemical industry is technologically viable by 2050.

Steel: Germany is the biggest steel producer in the EU and among the top ten worldwide. In 2020, steel production showed a decline in comparison to the previous year due to the effects of the COVID2019 crisis, which also affected the sales revenues. The steel sector is responsible for 30% of industrial emissions in Germany, which accounts for 52.9 million tons of CO_2 equivalent in 2019. The production installation using the blast furnace route emits almost 84% of the emissions within the industry, while the electric steel emissions are much lower at the rate of 13%. Although the German steel industry decreased its CO_2 emissions significantly (1/5) in the last 20 years, alternative innovations like clean (green) hydrogen use are needed for the decarbonization of the industry up to 95%. Additional decarbonization of the steel lies in the circular economy and steel recycling.

Ceramics: German ceramic industry is the second biggest in the EU. The industry requires high



energy use in terms of thermal and electric. The thermal energy consumption is the highest in the tile and brick industries. Moreover, natural gas is the most common fuel used in the entire ceramic industry, with levels around 95%. The emission from the ceramic industry is 3.36 million tons of CO_2 equivalent per year. The replacement of gas with solid fuels in ceramic burners is trending within the industry. Biomass and synthetic can contribute to further decarbonization in the industry. Although partial electrification of the burner could significantly reduce the CO_2, these technologies are neither available in the foreseeable future nor economically viable.

Glass: A yearly decline is seen in the glass industry revenues in Germany. In terms of revenues, the flat glass finishing and container glass sectors are the most important ones among many glass sectors. The different industry customers of these glass sectors include the construction industry, the food and beverage industry, and the chemicals, pharmaceuticals, and cosmetics industry. The Glass industry in Germany is one of the country's most energy-intensive industries, with an estimated emission of around 3.9 million tonnes of CO_2 in 2020. The melting process requires the most energy among all others that are mainly supplied by the combustion of fossil fuels and electricity. Glass industry in Germany achieved almost the maximum energy efficiency that is technically feasible. The climate-neutral future of the glass industry depends on the appropriate framework conditions and the preservation of competitiveness. Green hydrogen and electricity are crucial to achieving climate neutrality within the glass melting process.

Greece

Greece is not as heavily industrialized as other EU member states, however there is a significant presence and economic activity of several large EIIs, as well as several smaller companies. In some specific sectors, or sub-sectors the activity of Greek companies is actually relevant even on the EU level.



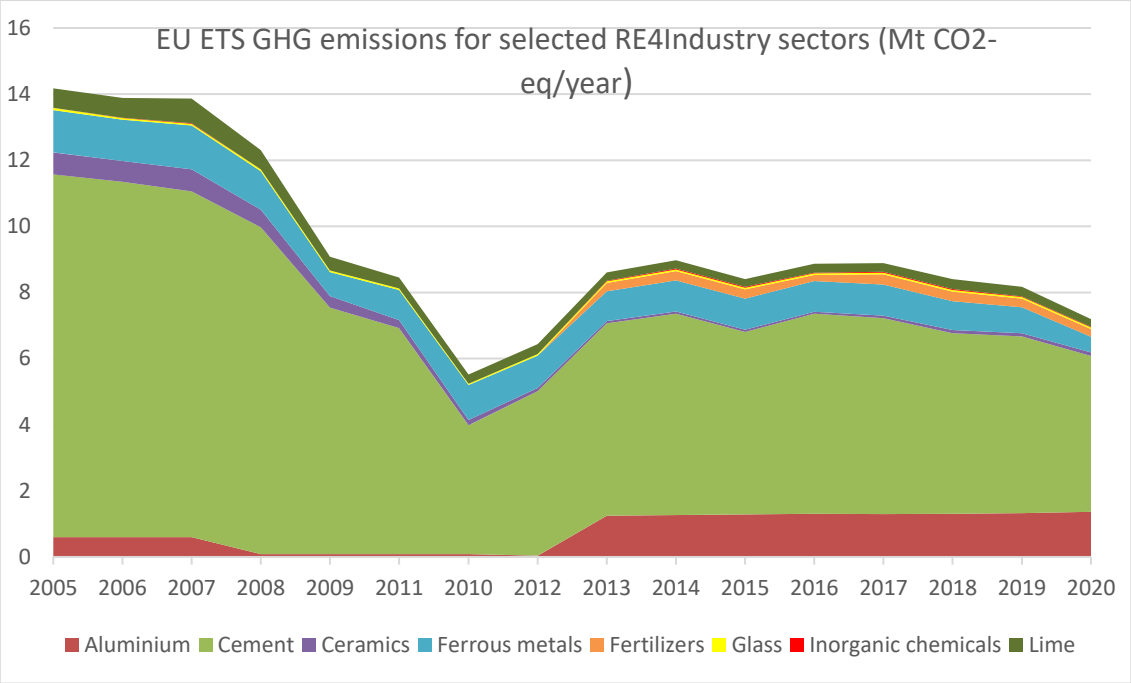


Figure 7- - EU ETS GHG emissions of selected RE4Industry sectors in Greece (https://re4industry.eu/eiis-interactive-map/)

As shown in **Error! Reference source not found.**, the power and heat sectors are responsible for the largest share in the GHG emissions of the Greek EU-ETS sector, but they were able to reduce their emission by 16.56 Mt or 46.78% since 2015. Aluminium (1.367 Mt CO_2-eq in 2020) and cement (4.709 Mt-eq in 2020) are the largest contributors, as illustrated in Figure 8. The ceramic industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015, however by observing the Figure 1, the sector has significantly decrease its CO_2 emissions since 2005.

Finally, in the period 2008-2010 there was a large fall in the CO_2 emissions of cement industry, which could easily assumed that is due to the economic crisis that faced Greece, which almost wiped out the construction industry and had as consequence the reduction of the cement production and therefore the reduction of the emissions in the production units.

Aluminium: The Greek non-ferrous metals industry consists mainly of one primary aluminium production company and one processing industry, this company is Mytilineos thought Aluminium of Greece and it is the largest vertically integrated alumina and aluminium producer in the European Union, with an annual production capacity that exceeds 182,000 tons of aluminium and 820,000 tons of alumina. The electricity needs of AoG correspond to around 320 MW, with an almost constant load profile. In 2020, the electricity consumption of the facility amounted to 2,840 GWh, corresponding to around 5.66 % of the total electricity consumption of Greece.

Cement: Cement production is a very dynamic industrial sector in Greece. The Greek cement industry employs about 3,000 persons and is concentrated in three companies: HERACLES (a member of Holcim Group), TITAN and Halyps (a member of Heidelberg Cement Group). Their annual production capacity is 6.7, 6.9 and 1.0 Mt/y respectively. Renewable energy solutions like the use of biomass are already implemented.

Lime: In Greece, the lime industry emits about 229,000tn CO_2, of which 75% are process emissions. It consists of 13 operating units and the annual production is around 400-500kt. Thermal energy demands covered primarily by petcoke. Some installations, usually smaller mainly in Southern Greece use biomass (exhausted olive cake).

Chemical: In Greece, the chemical industry is small. The only one industry at this time that is active is TOSOH HELLAS and it under the sub-sector of inorganic chemicals.

Fertilizers: The industry of fertilizers in Greece is also a small market. In Table 6 there are the two companies that produce fertilizers. They are both located in Nea Karvali, Kavala , in the same geographic area and the sum of CO_2 emissions reaches 235t in 2020. Hellagrolip S.A., since 2021 is under the brand name Kavala Fertilizers.

Steel: The first one and the most carbon intensive is LARCO GMMSA that produces ferronickel. The others are steel industries that do either secondary steel production by scrap iron smelting or rolling and wire processing.

Ceramics: The ceramics industry in Greece consists of 11 companies and produced 113kt CO_2 emissions in 2020. One of these companies, the "***Northern Greece Ceramics***" produces almost the half CO_2 emissions of them. In Greece, the produced ceramics are mainly bricks and tiles, the process emissions of this category reaches the 30% of total emissions and the rest are the emissions from fuel combustion and the indirect emissions (around 19%) has significant smaller share.

Glass: In Greece there is only one glass producer fall under EU-ETS that emits 47.3kt of CO_2-equivalents in 2020. Since 2015, the glass industry has remained stable regarding its CO_2 emissions.

Netherlands

The RE4Industry has selected steel, non-ferrous metals, chemicals, fertilisers, lime/cement, glass/ceramics as focus sectors. This paper summarises the status and decarbonisation plans of these sectors, as well as the main national policies, supporting these sectors in reducing dependence on fossil fuels.

Figure 8 shows the EU-ETS emissions of the selected large industries in 2020. The steel (5.80 Mton



CO_2-eq in 2020), fertilisers (5.07 Mton) and other chemical industry (9.25 Mton) are the largest carbon emitters. The fertilizer industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015; though these emissions stabilised from 2015 onwards. The large decrease of the emissions in the cement industry is directly related to the closure of the ENCI Maastricht plant that produced Portland clinker from its own marl mine.

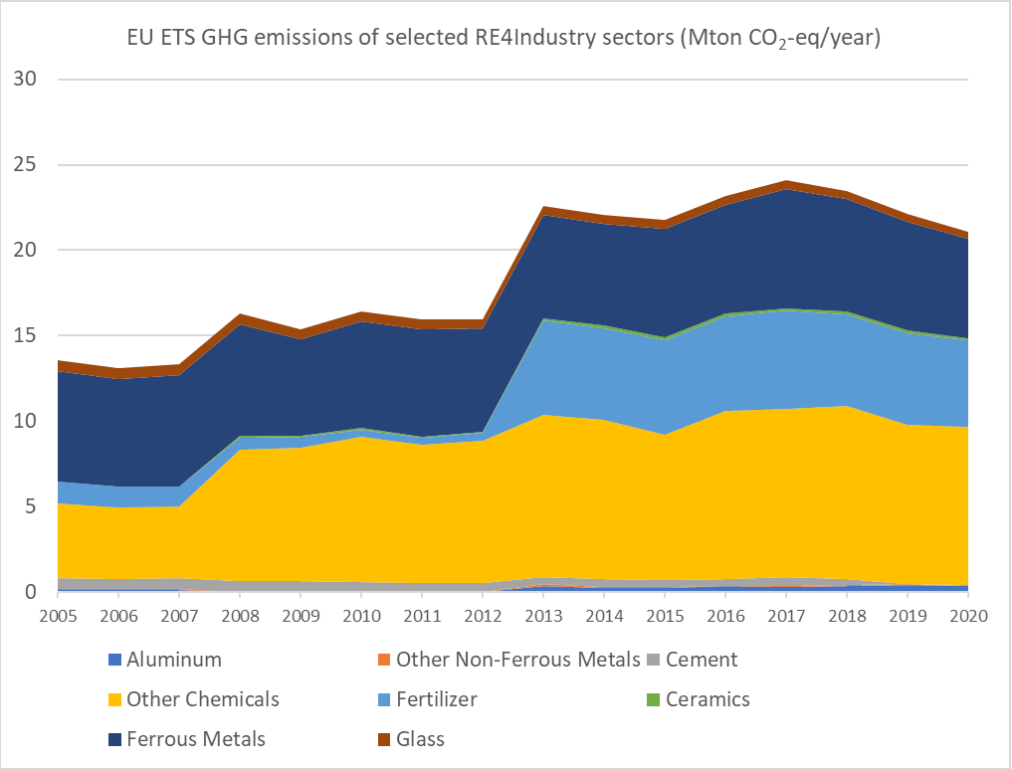


Figure 8: EU ETS GHG emissions of selected RE4Industry sectors in the Netherlands

The main GHG emitting companies and their plans to reduce carbon emissions are summarised below:

- Tata Steel IJmuiden is a large steel company with a carbon emission of 5.8 Mton in 2020. In Autumn 2021, Tata Steel Netherlands (TSN) decided to go for accelerated introduction of hydrogen-based steel making, via Direct Reduced Iron (DRI).
- Aldel in the North of the Netherlands (Delfzijl/Farmsum) is the only primary aluminium producer of the Netherlands, which has difficulties to deal with high electricity prices. They could be able to receive power from wind turbines without need to use the - heavily used - national grid.
- Companies active in the manufacture of “other chemicals” together emit 9.3 Mton of CO_2-equivalent. The three largest firms are Chemelot (Sittard Geleen), Shell Nederland (Moerdijk) and Dow Benelux B.V. (Hoek) together responsible for 83% of these emissions (7.7 Mton).

Renewable electricity and hydrogen play a major role in the decarbonisation plans of these industries, with a smaller role for CCU

- Chemelot and Yara Sluiskil are the two largest fertilizer companies, emitting 4.9 Mton of CO_2-equivalent per year. Their decarbonisation pathways depend heavily on the availability of renewable hydrogen. If sufficient hydrogen comes available, they could become suppliers of sustainable ammonia as shipping fuel.
- Sustainability strategies within the ceramic and glass industry mainly focuses on circularity aspects and energy efficiency measures, while renewable energy plays a less prominent role, often limited to reduction of scope 2 emissions by buying renewable electricity certificates.

Challenges and policies

Achieving the goals of the Climate Agreement and the further transition to an emission-free economy in 2050 require a significant expansion of the energy infrastructure. Realizing this in a timely manner is complicated. Industrial companies, network operators, energy producers and regional governments have jointly drawn up Cluster Energy Strategies (CESs) in 2021, covering five specific areas with existing industrial clusters, while the sixth is related to various sectors located throughout the Netherlands. These CESs are further governed by the National Infrastructure Programme for Sustainable Industry (PIDI) and the multi-year programme infrastructure energy and climate MIEK.

Hydrogen and electrification play a major role in the decarbonisation plans of the Dutch industry. Both options depend strongly on the availability of large volumes of renewable electricity. The renewable electricity capacity planned to be produced on land is elaborated in the 30 Regional Energy Strategies (RES). The RES strategies are expected to result in 35 TWh/year renewable electricity production by 2030. However, most renewable electricity will have to be produced by wind parks at sea. According to the Climate Agreement wind parks at sea with a joint capacity of 11 GW will produce 49 TWh/year by 2030. Given that in 2021 the capacity of wind at sea reached 2.5 GW and is expected to grow to 4.5 GW by 2030, a large effort still has to be made. The 35 TWh renewable electricity on land plus 49 TWh wind at sea as foreseen in the Dutch Climate Agreement of 2019 add up to 84 TWh of renewable electricity. This amount is well below the 128 TWh needed by the industry according to the Cluster Energy Strategies. Therefore, the advisory board “Additional Effort” as well as “Roadmap Electrification Industry” indicated that 45 TWh/year additional renewable electricity should be available by 2030, meaning that about 10 GW extra capacity of wind at sea should be realised, plus additional infrastructure to bring the electricity (or hydrogen if already converted at sea) to the (mainly industrial) users.



Spain

The Energy Intensive Industry sector is one of the most important activities in Spain. It accounts to around 23% (229 TWh) of the total energy consumption in Spain. The highest energy consumers sectors are the following: Chemicals, Iron & Steel, Non-ferrous metals and Paper & Pulp.

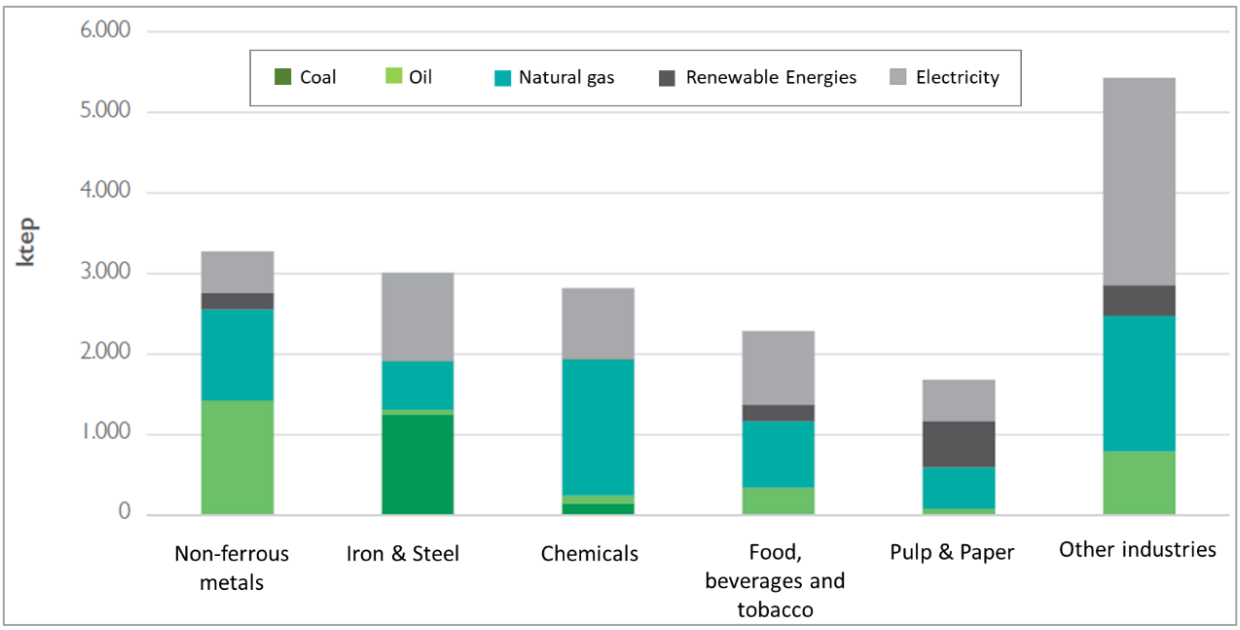


Figure 9 - Energy consumption in EII sector – Spain (ktep). Source: MITECO

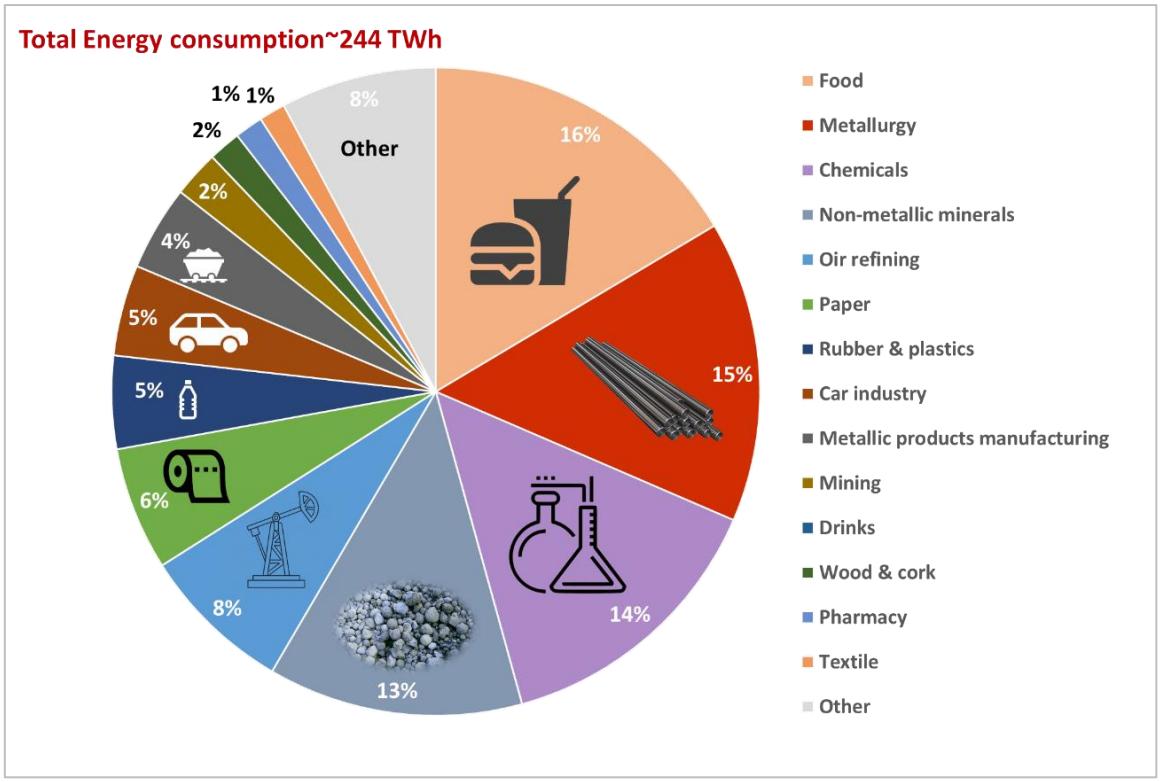


Figure 10 - Energy consumption by sector. Source: INE

Almost all the energy required for the intensive processes is provided by non-renewable sources, such as coal, oil and natural gas. Electricity plays a key role as well (ca. 22.6%), but renewable energies have a minor presence in the industrial energy landscape (less than 7%). Some characteristics of Spanish energy-intensive industry imposes on the industry further limitations to stablish decarbonisation measurements. For example, primary production process equipment for primary production processes is characterized by high initial investment costs and is designed with a very long service life, e.g., up to 50 years in the case of cement plants. The Spanish industry has made numerous efforts in the past, mainly due to its own need to maintain its economic competitiveness (and thus reduce the energy and CO_2 costs associated with its activity).

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100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

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Cement & Lime sector status in Europe

Author: Aimilia Lympeti, Manolis Karampinis

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Abbreviations

Abbreviation	Definition
CO_2	Carbon dioxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CRS	Central Receiver Systems
EII	Energy Intensive Industry
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
RE / RES	Renewable Energy / Renewable Energy Sources
PFRK	Parallel Flow Regenerative Kiln
PFR	Pre-heater kilns

1 Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe, focusing on the **cement & lime industrial sector**. The report aims to capture the current status of the cement and lime sector in Europe, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonisation.

Following this introduction, the report is divided in two chapters, the first one describes the cement industry and the second one the lime industry.

Each chapter gives a general overview of the corresponding sector and its importance for the European and global economy. The report provides information on the current usage and importance, the production processes, the energy and GHG emissions profile, as well as potential alternatives for mitigating their climate impact. Finally, they are presented the overall challenges and barriers that the cement and lime sector faces and potential measures and solutions for a decarbonised future.

The report is supplemented with four Annexes, which discuss the status of energy intensive industries in RE4Industry partner countries: Germany, Greece, Netherlands and Spain. Each Annex provides information regarding the main industries which are currently active in the sector, as well as any efforts and commitments undertaken regarding integration of renewable energy sources and decarbonisation in general.

2 Cement sector

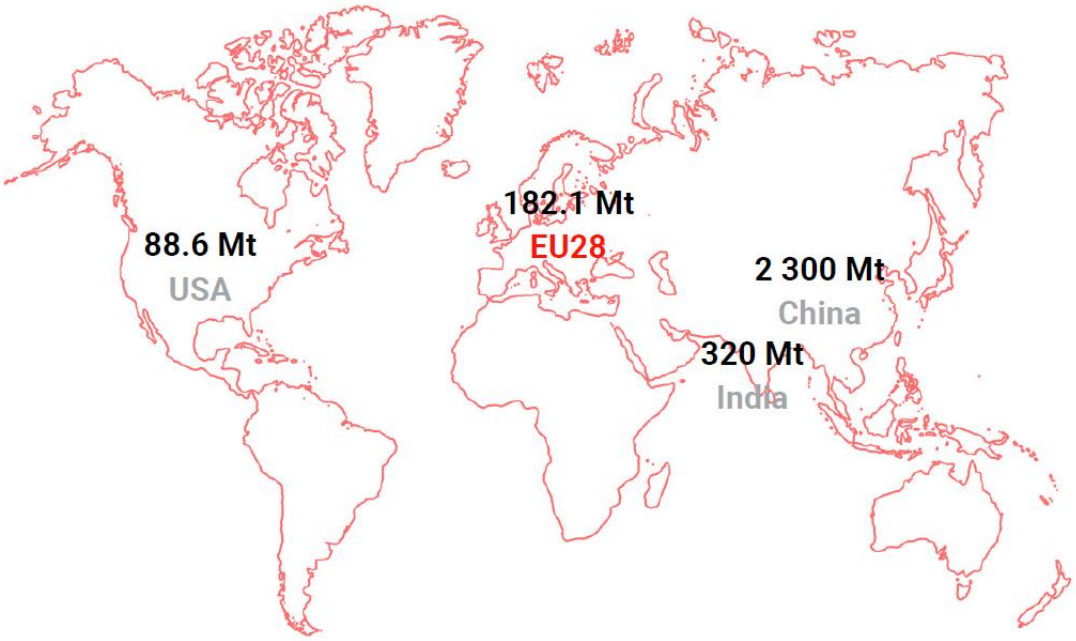
2.1 Introduction to cement industry

Cement is used to make concrete and concrete is the most-used manufactured substance on the planet in terms of volume. Concrete builds homes, schools, hospitals, workplaces, transport systems and infrastructure for clean water, sanitation and energy, consequently, cement plays a key role in our lives, in social and economic dimension.

Raw materials for concrete are abundant and available in most parts of the world. Concrete is affordable, strong, durable and resilient to fire, floods and pests. It has the flexibility to produce complex and massive structures.

The increasing global population, the urbanisation patterns and the infrastructure development will increase global cement production. The demand for concrete, and therefore for cement, is expected to increase, by 12-23% by 2050 compared to 2014, as economies continue to grow. There is no other material currently available that is available in the quantities necessary to meet the demand for buildings and infrastructure.

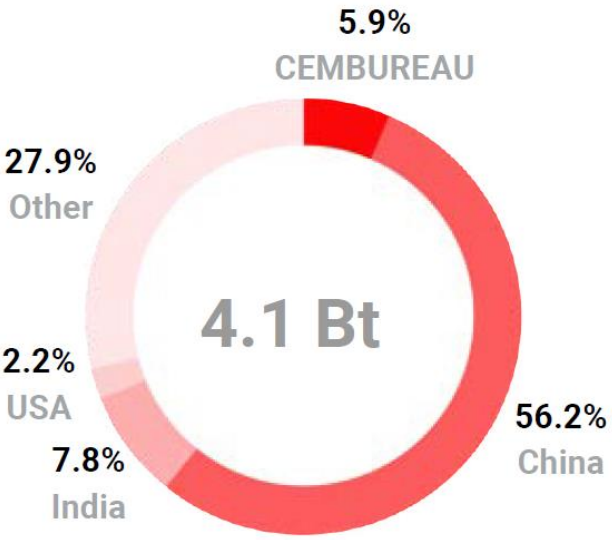
Figure 1 - Main world producers in 2019 [1]



According to Eurostat data, the cement manufacturing industry in the EU represented an estimated €15.2 billion turnover and €4.8 billion in value added. Germany, France, Italy, Spain, Poland and Belgium together accounted for 71% of EU's turnover, 70% of EU's enterprises and 68% of EU's

employment in the cement sector. In 2019, the sector offered employment to more than 47,000 [1] persons in Europe, distributed over around 350 enterprises.

Figure 2 - World cement production in 2019 [1]



The interests of the European cement industry are voiced by Cembureau (https://cembureau.eu/) which is the representative organisation of the cement industry in Europe. Currently, its full members are the national cement industry associations and cement companies of the European Union (except for Malta and Slovakia) plus Norway, Switzerland, Turkey and the United Kingdom. Croatia and Serbia are Associate Members of CEMBUREAU. Cooperation agreements have been concluded with Vassiliko Cement in Cyprus and UKRCEMENT in Ukraine [2].

2.2 History of cement

The origin of hydraulic cements goes back to ancient Greece and Rome. The materials used were lime and a volcanic. This formed the cementing material of the Roman mortars and concretes of more than 2,000 years ago and of subsequent construction work in Western Europe. Volcanic ash mined near what is now the city of Pozzuoli, Italy, was particularly rich in essential aluminosilicate minerals, giving rise to the classic pozzolana cement of the Roman era. So it was Roman Empire that accelerated the use of cement and this is shown by the fact that some of its most famous buildings still stand today including the Roman Pantheon (which remains the largest unreinforced concrete dome in the world) and the Coliseum. Although the cement that was used was different to today's cement material – the principle was similar [3]. Today Portland clinker based cement is the most common type of cement in use. Portland cement was first developed in the beginning of the 1800s.

2.3 Uses and properties

Whilst everyone knows the word cement, it is often confused with concrete or mortar. Cement is a key ingredient in both concrete and mortar, and it is always mixed with other materials before use.In particular cement is a glue which acts as a hydraulic binder, i.e. it hardens when water is added. It is primarily used to bind fine sand and coarse aggregates together in concrete. So if cement is mixed with water, sand and gravel forms concrete, which is what the vast majority of cement is used for and if cement is mixed with water, lime and sand forms mortar.

Cement is used to make concrete, the most consumed manufactured substance on the planet. The overwhelming applications of concrete are linked to construction and civil engineering sector. Concrete's remarkable properties make it a vital element and are the reasons that made cement so widespread.

The followings are some of its incredible performance benefits of concrete linked with cement's properties:

Availability	Concrete is an abundant, local and cost-effective building material which makes it available and sustainable both in developed and in emerging economies.
Carbon uptake	Concrete reabsorbs a significant amount of CO_2 over its lifetime in a process known as carbon uptake or recarbonation.
Circular economy	The industry utilizes recycled/ secondary aggregates and cementitious industrial byproducts in concrete and alternative fuels/raw materials in cement kilns. Concrete buildings are long-lasting and can be re-used or adapted and re-purposed.
Design for disassembly	Certain concrete buildings can be designed and built for easy disassembly as to enable the reuse of its component parts in other construction projects, reducing use of raw materials and lowering waste.
Disaster resilience	Concrete stays standing more often than alternative building materials in the face of disaster, reducing the need for reconstruction and enabling communities to recover more quickly
	Concrete buildings last longer and require less maintenance. They

Durability	better survive disasters and can be reused many times over in their lifetime, meaning less demolition and reconstruction.
Fire resistance	Concrete's resistance to fire improves the safety and minimises damage, so buildings can return to use quickly, boosting community resilience.
Passive cooling using thermal mass	Due to its ability to absorb and store heat, concrete can be used to passively heat or cool buildings, reducing the energy consumed by heating or air conditioning as well as reducing the risk of overheating.
Strength	Society expects the built environment such as buildings, bridges and other infrastructure to be enduring and safe. Concrete is well known for its attributes of strength, durability, resilience and safety.
Structure as finish	Concrete as a finished surface (e.g. ceiling, wall or floor) lowers material usage in construction and future maintenance needs.
Versatility	Concrete is a hugely versatile material, allowing structural designers to meet and optimise application requirements with concrete in the most sustainable manner.

More importantly, cement and concrete are pivotal to building a climate neutral Europe.

Cement is obtained by grinding cement clinker and, in some cases, supplementing it with additions. Clinker is produced through the firing/sintering (in a cement kiln) of a mixture of limestone (or other minerals containing high levels of calcium) and other materials (e.g. clay, shale, sand, iron ore, bauxite, fly ash and slag) to provide the necessary final chemical composition. A typically cement (Portland) clinker mix would contain approximately 80% limestone and 20% clay. Clinker is a nodular material before it is ground up, nodules can be anything from 1mm to 25mm or more in diameter [4].

Portland cement, which is the most common type of cement, is a calcium silicate hydraulic cement produced from grinding (Portland) cement clinker to a fine powder with a small addition of gypsum (normally 3 to 5%). Portland cement is normally grey in colour but may also be white. The European cement standard EN 197-1 provides a classification of common cements based on Portland cement clinker with one or more other main constituents. The standard defines 27 distinct common cement products and their constituents grouped into five main categories [4].



These categories reflect the relative proportions of cement clinker and other main constituents, as follows:

- CEM I **Portland cement** (>95% clinker);
- CEM II **Portland-composite cement** (65-94% clinker, and 6-35% other constituents[10]);
- CEM III **Blast-furnace cement** (5-64% clinker, and 36-95% blast-furnace slag);
- CEM IV **Pozzolanic cement** (45-89% clinker, and 11-55% of silica fume or, pozzolana or fly ash or a combination thereof);
- CEM V **Composite cement** (20-64% clinker, and 18-50% blast-furnace slag, and 18-50% pozzolana or siliceous fly ash or a combination thereof).

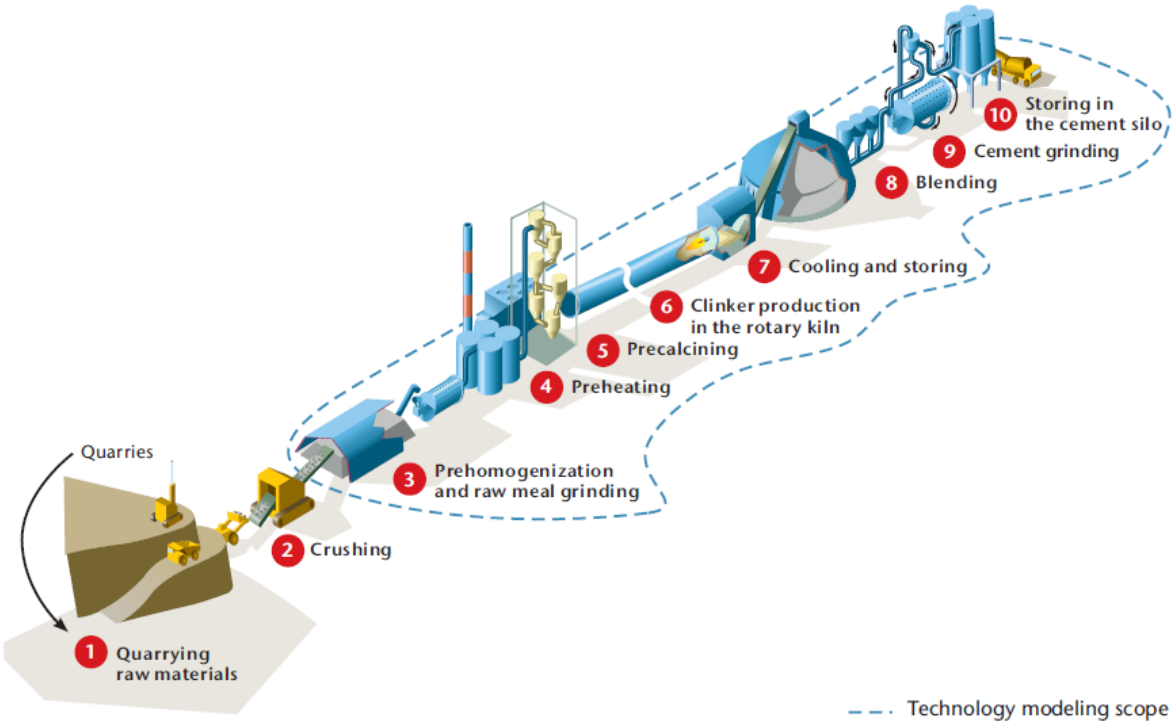
Concrete is a mixture of cement, water and aggregates and in some cases a small amount of ingredients called admixtures. Aggregates make up approximately 60-75% of the mixture and cement and water make up the rest. Aggregates are usually inert coarse materials like gravel, crushed stone, sand or recycled concrete. The type of aggregate selected depends on the application of the concrete.

2.4 Production process

Cement production involves multiple stages and actors from the quarry to the final product. Cement production is a three-stage process: raw materials preparation, clinker production and clinker grinding with other components to produce cement. Different raw materials are mixed and milled into a homogeneous powder, from which clinker is produced in high-temperature kilns where direct emissions of CO_2 occur. Clinker is then interground with gypsum to produce cement. Other components, including fly ash, ground granulated blast furnace slag (GGBFS) and fine limestone, can be interground or blended, depending on the required technical properties of the finished cement.



Figure 3 - Dry production process of cement [5]



Main stages of cement's production process:

1. **Extraction:** The first step is to extract blocks of raw material (limestone, chalk or marl) from quarries. These mostly consist of limestone (approx. 90%), but sand, clay, bauxite and iron ore may be added to reach the desired chemical composition. Because of the high transportation costs, cement plants are typically located close to the quarries.
2. **Crushing:** Primary raw material (limestone) in boulder form is transported to primary and secondary crushers and are broken into smaller pebble-sized chunks, typically to less than 10 centimeters in size.
3. **Preparing raw meal:** Raw materials are mixed to achieve the required chemical composition in a process called "prehomogenisation". After they are homogenized and they are pulverized into a thin powder call "raw meal".
4. **Preheating:** Hot exhaust gases coming from the kiln preheat the powdered raw meal before it enters the kiln, this improves the efficiency of the process and reduces fuel needs.
5. **Precalcining:** Calcination is the decomposition of limestone ($CaCO_3$) to lime (calcium oxide: CaO), releasing carbon dioxide, and subsequent reaction with the other constituents from the raw material to form cement clinker. There are both 'wet' and 'dry' production

technologies for cement clinker, plus intermediate semi-dry/semi-wet. However, in Europe almost all production is based on 'dry' technologies, which are less energy intensive, with wet kilns being phased out. It takes place in a "precalciner" in most processes which is a combustion chamber at the bottom of the preheater above the kiln, and is partly in the kiln. Approximately 65% of all fuel is burnt in this step of the process, in plants with precalciner technology.

6. **Production of clinker in the rotary kiln:** pre-calcined meal is fed into the kiln and fuels as coal, petroleum coke, gas, oil and alternative fuels are fired directly into the kiln to heat the raw meal to temperatures of up to 1450°C, thus allowing its sintering into clinker. The reactions in the kiln include completion of the calcination of limestone that has not taken place in the precalciner and production of CO_2 emission. The CO_2 released from the raw materials during production is referred to as "process CO_2 emissions".

$$CaCO3 + heat \longrightarrow CaO + CO_2$$

7. **Cooling and storing:** Hot clinker from the kiln is cooled from over 1000°C to 100°C rapidly on a grate cooler, which blows incoming combustion air onto the clinker. The air blowers use electricity and heated blown air circulation to improve thermal efficiency. A typical cement plant will have clinker storage between clinker production and the cement grinding process.

8. **Blending:** Clinker is mixed with other mineral components to make cement. All cement types contain around 4-5% gypsum to control the setting time of the cement. Slag, fly ash, lime-stone or other materials can be interground or blended to replace part of the clinker. This produces blended cement.

9. **Grinding:** The cooled clinker and gypsum mixture is ground into a grey powder, known as Portland cement (PC), or ground with other mineral components to make blended cement. Ball mills have traditionally been used for grinding, although roller presses and vertical mills are often used in modern plants due to their greater energy efficiency.

10. **Storing:** The final product is stored in cement silos and later can be packed in bags or loaded in bulk for transportation to customers.

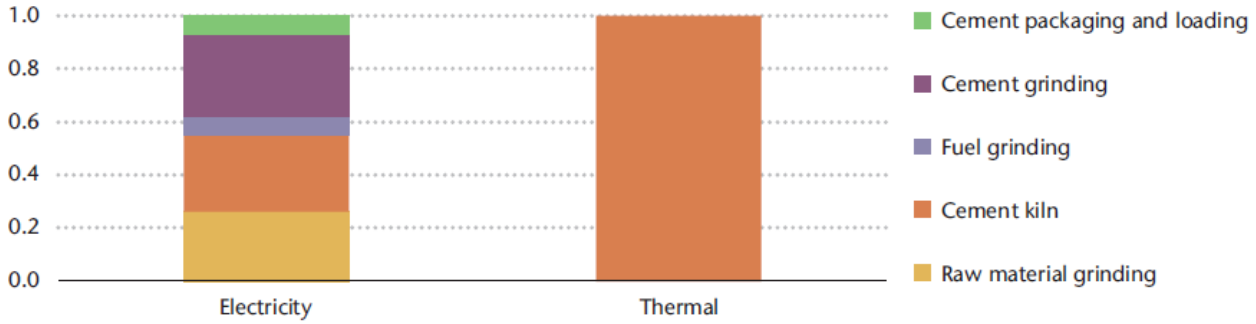
2.5 Energy and CO_2 Emissions

Every stage of the cement manufacturing process requires energy. Almost 50-60% of the total production cost is linked to the energy costs, which explains why cement industry is considered an



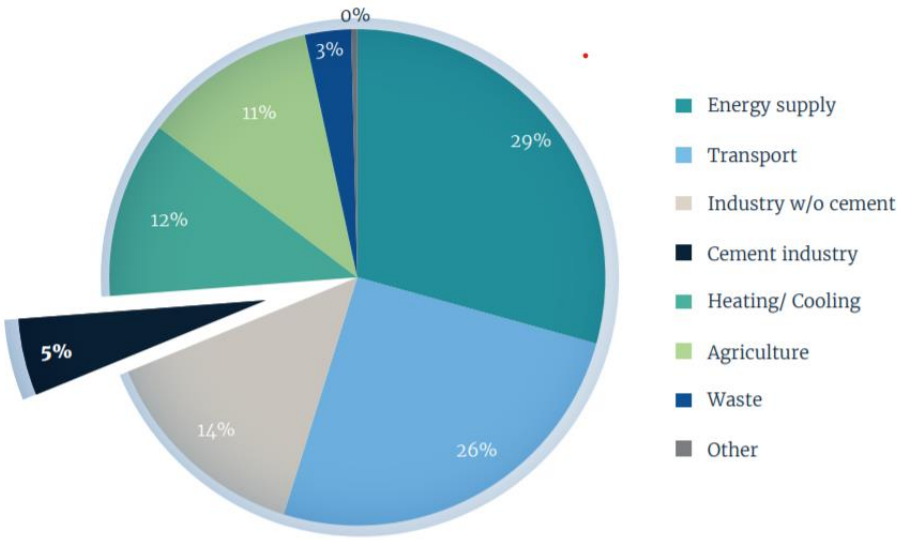
energy intensive industry. Thermal energy accounts for about 20–25% of the cement production cost. The typical electrical energy consumption of a modern cement plant is about 110–120kWh per tonne of cement and requires 60 to 130 Kg of fuel oil or its equivalent, depending on the cement type. Electricity is used to run grinding and loading equipment, and fuels are used to provide the thermal energy needed in the kiln and precalciner for the chemical reactions required to produce clinker [6]. The dry process uses more electrical but much less thermal energy than the wet process. In industrialized countries, primary energy consumption in a typical cement plant is up to 75% fossil fuel and up to 25% electrical energy using a dry process. In 2017, electrical energy represented 13% of total energy use and 6% of total CO_2 emissions related to cement manufacturing according to Cembureau.

Figure 4 - Energy demand distribution by process step [7]



Cement production is responsible for 5% of total CO_2 emissions, and the steel used in construction represents a similar amount. So, the construction sector represents a major share of European greenhouse gas emissions (GHG). The two main construction materials represent approximately 10% of the total European CO_2 emissions. [8].

Figure 5 - EU OECD countries' CO_2 emissions by sector [8]



The cement industry is an energy-consuming industry in which carbonate (CaCO3) decomposition releases a large amount of CO_2 and produces 0.6 tonnes of CO_2 when producing a tonne of cement.[9] Thus, the clinker production process generates direct CO_2 emissions due to fuel combustion and the carbon released from raw materials.

The cement industry has been one of the highest energy consuming and CO_2 emitting institutions worldwide (rated third worldwide), and while improved techniques and modern technologies have brought an increase in efficiency of production, reduced energy consumption and reduced CO_2 emissions, a rise in CO_2 continues particularly as a consequence of increased demand for infrastructural development [8]. The sector has the second-largest share of total direct industrial CO_2 emissions, at 27% (2.2 Gt CO_2/ yr.) in 2014. [7]

Consequently, cement manufacturing is a CO_2 intensive process. Limestone, a key raw material, emits CO_2 at the high temperatures needed for production of Portland cement clinker. These process emissions account for around 60% of total CO_2 emissions. The remaining 40% of CO_2 emissions arise from direct and indirect energy emissions, i.e. the combustion of fuels required to generate the necessary heat (direct emissions) and any emissions from electricity generation (indirect emissions). An interesting point is that approximately 65% of all fuel is burnt in the step of precalcining.[7].

The European cement industry has actively worked on reducing emissions for a long time. Since 1990, it has reduced its CO_2 relative emissions by about 15%.

Over time it will be possible to significantly reduce the energy emissions in cement manufacturing through fuel substitution with other sources of energy. Reduction of process emissions needs significant technological innovation, both in the manufacturing to reduce their release in the first place, and through carbon capture technology. Action is already being taken in both these areas, but more work is required, and the industry is already investing heavily in research and innovations to reduce these emissions.

Finally, it is important to note that concrete also acts as a carbon sink over its lifetime as it absorbs and stores CO_2 emitted in the production of its ingredients. Reports shows that across the inventory of all concrete, an average of up to 25% of the process emissions emitted during cement manufacture is reabsorbed by concrete during its lifetime.[11]

Figure 6 - The 5C approach [12]



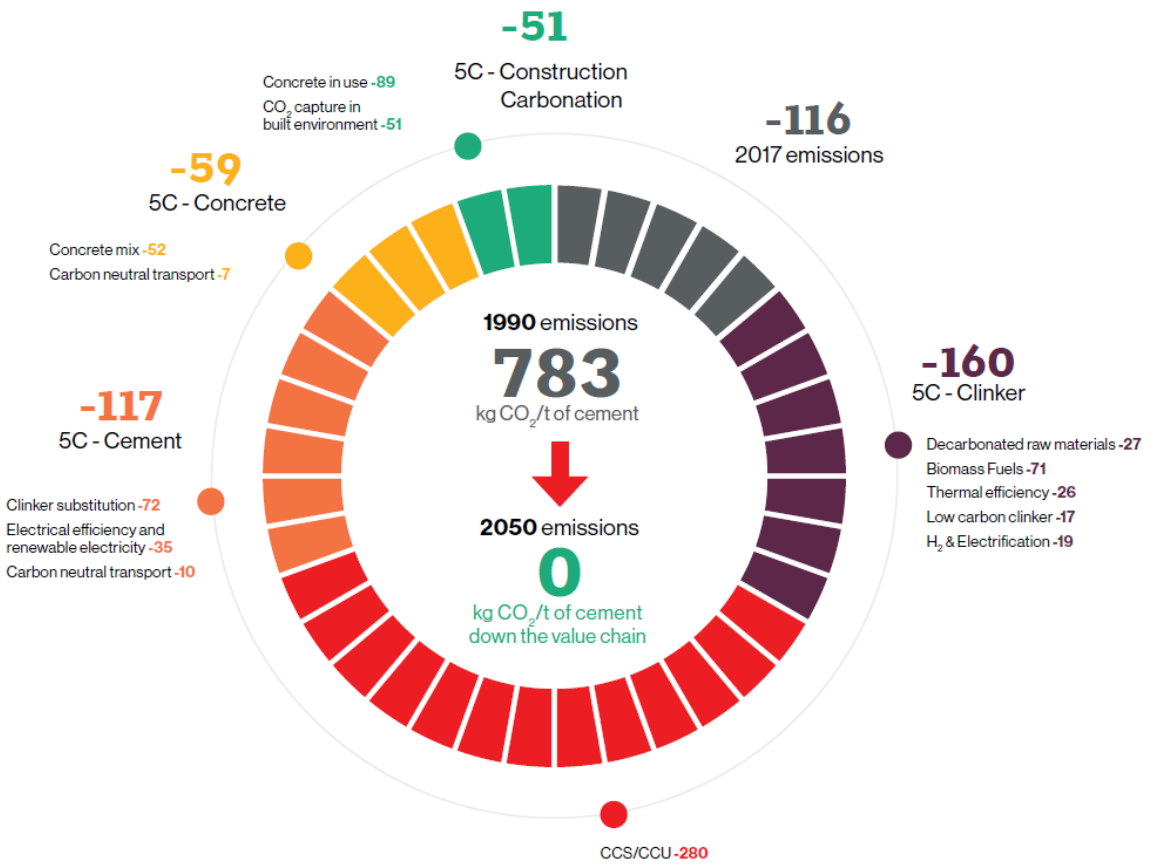
To date, the main efforts to reduce CO_2 emissions have focussed on the cement level, however, further savings can be achieved by considering the entire value chain, from cement production to its final use in the construction site in mortars and concrete. This is the “5C approach” that promotes a collaborative approach along the clinker-cement-concrete-construction- carbonation value chain involving all actors to help turn the low carbon vision into reality.

The main steps to achieve carbon neutral concrete is by:

- Eliminating our direct energy related emissions and maximizing the co-processing of waste from other industries, which substitutes the use of fossil fuels involved in cement manufacture.
- Reducing and eliminating indirect energy emissions through renewable electricity sources where available.
- Reducing process emissions through new technologies and deployment of carbon capture at scale.
- Reducing the content of both clinker in cement and cement in concrete, as well as more efficient use of concrete in buildings and infrastructure
- Reprocessing concrete from construction and demolition waste to produce recycled aggregates to be used in concrete manufacturing
- Quantifying and enhancing the level of CO_2 uptake of concrete through recarbonation and enhanced recarbonation in a circular economy, whole life context.

The below chart (Figure 7) of CEMBUREAU summarizes the technical pathways to achieve net zero emissions compared to the 1990 CO_2 emissions.

Figure 7 - CEMBUREAU Roadmap CO_2 reductions along the cement value chain (5Cs: clinker, cement, concrete, construction, re-carbonation)[13]



2.6 Technology measures

The most energy intensive phase of the value chain is at the cement plant, where two critical materials are produced: clinker and cement. Cement production is a 24/7 process and is naturally energy intensive. Concrete on the contrary is a construction material with one of the lowest energy and carbon content, however, the manufacture of its key component, cement, is CO_2-intensive.

Carbon neutrality along the cement and concrete value chain requires the deployment of existing and new technologies. This report will focus on the technologies that could be applied during the production of clinker, cement and concrete.

Clinker

Clinker is produced through a chemical reaction referred to as calcination. During calcination raw materials like sand and clay, together with limestone are heated up to 1450°C in a rotary kiln where limestone is decarbonized producing clinker which is then grounded down to fine powder. This chemical process causes 60%-65% of cement manufacturing emissions (process emissions).

The remainder of CO_2 emissions comes from the fuels used to heat the kiln (combustion emissions).

In order to reduce emissions linked with clinker production there are some potential measures:

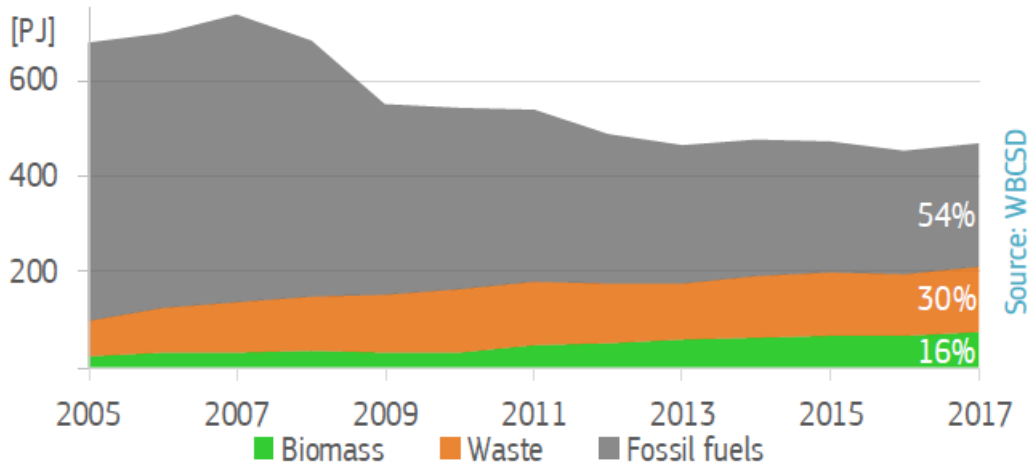
Alternative Decarbonated Raw Materials

Waste materials and by-products from other industries can be used to replace some of the limestone. These materials can include recycled cement paste from demolition waste, air-cooled slag and waste lime, recycled concrete. These materials, such as the fine material from recycled concrete, do not emit CO2 when heated because they have already had the CO_2 removed. Globally this is forecast to provide a 2% reduction in total emissions from the sector.

Fuel Substitution

Fuel emissions account for approximately 35% to 40% of total CO_2 emissions from cement manufacturing. In producing cement we simultaneously recover energy and recycle minerals from a variety of waste streams (Co-processing) and use biomass. In 2017, alternative fuel use represented 46% of the total fuel needs of kilns across Europe of which 16% was biomass.

Figure 8 - Evolution of use of biomass through last years



It is feasible the use of alternative fuels to be over 90% if the materials are locally available. In fact, several plants do achieve that level thanks to the correct regulatory environment, public acceptance and investment support [13].

Moreover the use of **electrical heating**, plasma or solar energy to calcine the raw materials could result in the future in saving 55% of the fuel CO_2 if **renewable electricity** is used. Combined with the **use of hydrogen** and **biomass** fuels for the clinker process, this could result in near zero fuel CO_2 emissions.

Thermal Efficiency

Cement kilns are already efficient, typically operating at levels between 70 to 80% efficiency. However, improvements can still be made to the thermal efficiency of some of our kilns through converting preheater and other kiln types to precalciner kilns and by recovering heat from the cooler to generate up to 20% of electricity needs for the cement plant [13].

New types of Cement Clinkers

Another alternative measure to reduce the emissions is the use of new types of cement clinkers which are chemically different from conventional Portland cement clinker. These result in 20 – 30% CO_2 savings by reducing the amount of limestone in the formulation and because they require less energy. However, the cements that came from theses clinkers have different properties so they can only be used for specific applications.

Carbon Capture and Utilisation/Storage (CCUS)

In order to fully decarbonise the sector, process emissions from the clinker-making process need to be addressed, regardless of the heat source. Part of the solution will need to be CO_2 capture – applied to both the combustion and process emissions, or combining a zero-CO_2 heat source with the capture of concentrated process emissions.

Carbon capture, utilisation and storage (CCUS) describes processes that capture CO_2 emissions from industrial sources and either reuses or stores it so it will not enter the atmosphere. Carbon capture is still expensive today, but technology is improving and the significant number of demonstration facilities, currently being deployed in cement production, demonstrates the potential for significant cost reduction in the years ahead. However, not all plants will be suitable for CO_2 capture since the distance to the storage sink may be too far, however, in those cases mineral carbonation should be considered. The choice of technologies will depend on their techno-economic competitiveness, and will vary depending on the availability of renewable electricity and waste heat recovery and integration. The following CO_2 capture technologies have been developed so far: calcium looping, oxyfuel, chemical absorption (e.g. amines), direct separation, mineral adsorption and CO_2 use technologies (e.g. enhanced concrete recarbonation, mineralisation) [13], [14].

Therefore, we can say that the binder of the future will recapture its own emitted CO_2 during the production, use, recycling and upcycling phases. In other words, the binder of the future will allow full closure of the CO_2 loop.



Ultimately, it is believed that the deployment of carbon capture technology at full scale during cement manufacturing could fully eliminate its process emissions and potentially result in the future delivery of carbon negative concrete [14].

Cement

Cement is producer after the mixture of the produced clinker gypsum and clinker substitutes. All these are then grounded to the correct fineness to create cement. At this stage there are no further CO_2 emissions, however, electricity is used for grinding and mixing and transporting the incoming materials as well as final cement products. The amount of CO_2 emissions generated from this electricity could be decreased by using electricity from renewable sources. As far as concerns the decrease of emissions related to cement itself there is the option of using low ratio clinker cements or even alternatives to clinker.

Low Clinker Cements

The ration of clinker in cement was about 77% in 2017. The other 23% is substituted by alternative materials like granulated slag from steel blast furnaces and fly ash from coal-fired power plants. However, due to the phase-out of coal fired power plants, the supply of fly ash (currently 10% of total substitutes) and the use of slag from the steel sector (currently 33% of total substitutes) will decrease. Already today, 21% of the total substitutes are natural pozzolans, limestone or burnt oil shale and non-traditional substitutes such as calcined clay and silica. So further research is looking for new materials which could be used in the future such as pozzolan materials from waste streams and slag from other industries. Depending on national legislation and market conditions, these substitutes can also be added at the concrete manufacture stage [13].

Concrete

Concrete is the main end-product of cement, it is manufactured by mixing cement(10-15% in this mix) with water and aggregates with small quantities of chemical admixtures used to improve the properties of the concrete and to meet specific product requirements The direct CO_2 emissions related to concrete largely come from cement production.

In terms of concrete production, **industrialisation** is the key specific lever. Moving from small project site batching of concrete using bagged cement to industrialised processes offers significant CO_2 emissions savings because of the adherence to mix specifications and quality control.

Also, improved data and data processing will enable builders to get the exact amount of concrete delivered on site to get the job done and the **digitalisation** can also help improve aggregates grading and optimise admixtures.



Finally the **decarbonisation of electricity** will play a key role since it will result in emissions from generation of electricity used in clinker, cement and concrete production to be reduced to zero. Taking into account that the demand for electricity from the sector will increase due to the increased total production (2030) and the electricity demands for carbon capture (2050) it is important to focus on this [14].

2.7 Challenges – Potential measures

In order to reach the target of net zero emissions is important to overcome the challenges that follows the above measures. All these measures needs a time framed strategic plan in order to be feasible and sustainable. In this transition consumers must learn and accept to make new choices and change certain habits and simultaneously governments, at all levels, will have to change regulation, support and invest in industries and industry in turn, will have to change the way products are made. Therefore, it is of crucial importance to act rapidly and to create the right regulatory and financial framework.

For supporting the research and development of breakthrough technologies as well as the acceleration and scaling-up of proven efficient low carbon technologies, with a particular focus on CCUS and new and alternative binders, policies should help mitigate the risk through investment mechanisms that allows investments against reasonable returns. Consequently, investments in state-of-the-art technology for new and retrofit plants will require innovative forms of funding and updated State Aid rules, and since the cement industry has long-term investment cycles, continued EU funding and innovative sources of financing, such as carbon contracts, will be key for the roll-out of low-carbon technologies. Hence investment in decarbonization projects require regulatory stability and legal certainty. Moreover energy intensive industries, including cement, will need sufficient infrastructure to transport, re-use and store the CO_2 captured. The EU should urgently look at developing a pan-European CO_2 transportation network that responds to the industry's needs [13].

The European cement industry has actively worked on reducing emissions for a long time. Since 1990, it has reduced its CO_2 relative emissions by about 15%, so it is ready to play its role, especially when it comes to making the circular economy work. With 46% of its fuels now replaced by alternative fuels sourced from a variety of waste streams whereby waste is used to simultaneously recover energy and recycle the mineral content, which is known as co-processing, the cement industry is an essential player in the circular economy. This is equally the case from a downstream perspective where concrete is fully recyclable at the end-of-life of a built structure and CO_2 released during the cement manufacturing phase is re-absorbed at the end of the value chain through re-carbonation.



As far as switching to alternative fuels and phase out the use of fossil fuels it is necessary the industries to have access to non-recyclable and biomass waste. For that reason policies should facilitate waste shipment between EU countries, discourage landfill and minimise exports of waste outside of the EU. In addition, sufficient access to biomass and non-recyclable waste should be guaranteed for co-processing in cement kilns, as the most ecological solution for the majority of materials [13].

Another challenge that may face the measures that lead to this transition is that community many times doesn't accept the alternative fuels, CCUS, and other manufacturing technologies. Misinformation and lack of awareness about the risks and benefits of cement manufacturing and materials technology can create community opposition to improvements that benefit surrounding communities through fewer environmental releases, waste diversion, reduced land-disposal and associated public health and environmental impacts. Policymakers and regulators can help reduce opposition resulting from misinformation through environmental justice and public education programs.

When it comes to low CO_2 cements, it is important to motivate industries to develop these types of cement .Green public procurement and the upcoming EU sustainable product policy offers key opportunities in this respect. The EU will accelerate the adoption of low-carbon cement and concrete products through changes in public procurement standards and policy. This is done by ensuring the timely adoption of product standards to allow the release of low carbon cement and concrete on the market and facilitating access to raw materials that allow lower CO_2 cements.

Another aspect which is really important to all energy intensive industries and cement industry as one of them is the price of renewable energy and in general the electricity price, since all energy intensive industries are sensitive to the electricity price and price instability could create uncertain investment climate. In order to boost the supply, distribution, availability and affordability of renewable energy it needs to make renewable energy affordable for industry. The electrification of industry should be encouraged through tax exemptions for electricity use in industrial processes (Energy Taxation Directive) or appropriate compensation mechanisms (State Aid Guidelines).

Additional, governments should pursue efforts towards developing stable and effective international carbon pricing mechanisms complemented by interim financial stimulus packages that compensate asymmetric pricing pressures in different regional markets. While a considerable proportion of cement production is not exposed to cross-border competition, it is crucial that carbon pricing mechanisms are coupled with measures that ensure local lower-carbon cement production remains competitive against higher-carbon cement imports.



Finally, in order to success this environmental goal, scientists and R&D departments will play their significant role. It is crucial for a successful transition to take all workers on the climate neutrality journey and strongly focus on training and skills development. The upcoming Sustainable Built Environment strategy should promote cooperation between architects, local authorities and engineers. It should foster skills and training to deliver energy-efficient designs and lower-carbon concrete mixes.

3 Lime

3.1 Introduction to lime sector

Calcium carbonate ($CaCO_3$), is a raw material that is widespread and comprises more than 4% of the earth's crust. The feedstock for lime production is calcium carbonate and/or calcium magnesium carbonate. Calcium carbonate is used to produce lime and calcium magnesium carbonate is used to produce dolime respectively. Calcium carbonate can be found in chalk, limestone and marble whereas dolomitic calcium carbonate can only be found in dolomite.

The key sustainable development issues for the extraction of the main raw materials for lime production reside in the access to high quality limestone and dolomite deposits to secure geological reserves for a long term future. Geologically, limestone is a common stone. However, it is rare to find deposits which contain sufficient amounts of resources with high chemical purity and the right physical and mechanical properties [15].

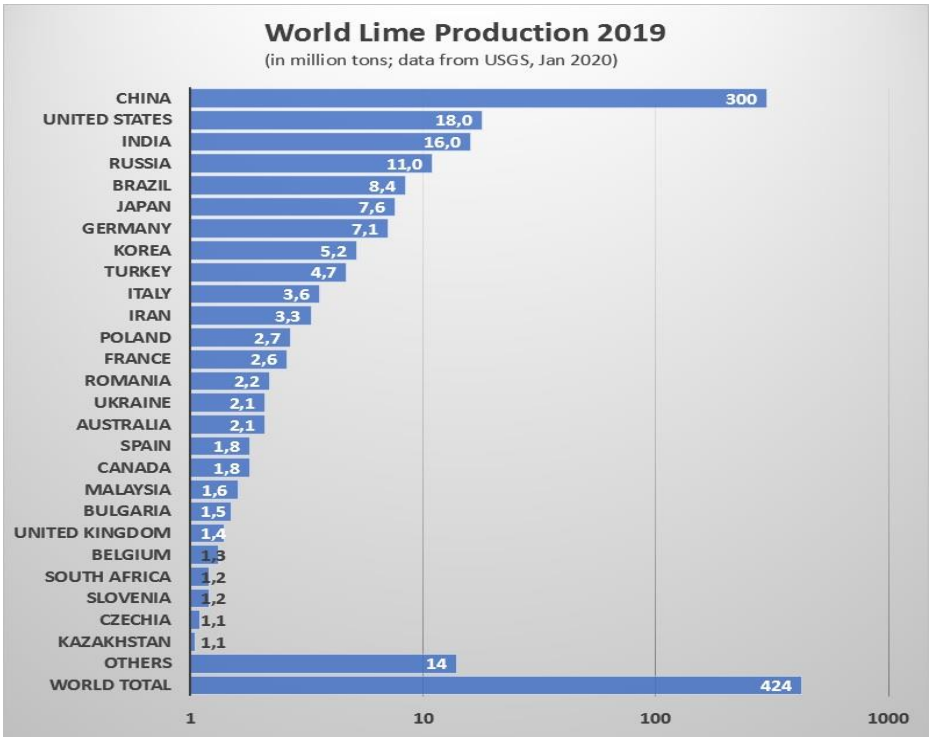
Lime is forming through a calcination process, a thermal decomposition process where limestone ($CaCo_3$) or dolomite $CaMg(CO_3)_2$ under the influence of high temperatures, release carbon dioxide and are converted into lime (CaO) and dolime ($CaMgO_2$). This lime production leads, due to the process itself but also due to heat requirements, to emissions of greenhouse gases. In 2012, the total CO_2 emissions of the European lime industry were around 0.6% of the total European greenhouse gas emissions [16]. Regarding the CO_2 emissions of lime industry, although the past years the emissions have dropped, due to the efforts made for modernising the plants and changing the fuels mix, it is not enough. So, the lime industry is searching for more options, with focus on carbon capture since the bulk of the emissions come from limestone and it is inevitable to reduce such emissions.

Today, lime is used in a wide range of applications and is necessary to many other sectors like constriction, chemical industry, iron and steel industry and agriculture. Furthermore its properties facilitate other industries to reduce their carbon footprint.



The total world production in 2020 was 420,000t and around 6% of them was the EU production, with Germany, Italy, Poland and France being the largest producers of lime. The undisputed dominant however, is China with its production reaching the giant amount of 300,000t of lime annually [17]. Regarding the size of industries, the most lime industries in EU are categorized as small to medium size companies and in 2020 there were operating almost 170 plants [18].

Figure 9 - World lime production 2019, Source: International Lime Association



The interests of the European lime industry are voiced by European Lime Association (EuLA, https://www.eula.eu/). Currently, the association is representing 21 national organisations, and approximately 50 companies. The European lime industry employed around 11,000 people directly and produces circa 23 Mt of lime and dolime.

3.2 History and applications of lime

It is not known exactly when lime was first discovered from human. It is assumed that limestone rocks were used to protect the fireplace of humans. Fire heated the rocks and the first burnt lime was created. It then rained and the lime slaked into calcium hydroxide. There is also evidence that the use of quicklime (CaO) and hydrated lime (Ca(OH)2) in construction was widespread as early as 1000 B.C. among many civilisations, including the Greeks, Egyptians, Romans, Incas, Mayas, Chinese, and Mogul Indians. The Romans even knew of its chemical properties and used it, for example, for bleaching linen and medicinally as limewater [15].

A frequent cause of confusion is due to the wrong use of the term “lime” to describe limestone products. The term “lime” includes quicklime (also “burned lime”) which is the calcium oxide (CaO) produced by the decarbonisation of limestone (CaCO3) and slaked lime, which is produced by the reaction of quicklime with water and consists mainly of calcium hydroxide ($Ca(OH)_2$). The 90% of total produced amount is lime and 10% is dolomite.

Lime products are used in a wide variety of applications in Europe, and worldwide and it is irreplaceable for many industrial sectors, from steel manufacturing to construction materials, chemical industries and paper pulp. Its highly importance and diverse substance is due to its alkalinity and ability to purify and neutralise. The average EU citizen indirectly uses around 150 g/day of lime products.

Figure 10 - Overview of lime customer markets (sales by sectors 2018), Source: EuLa Database 2019

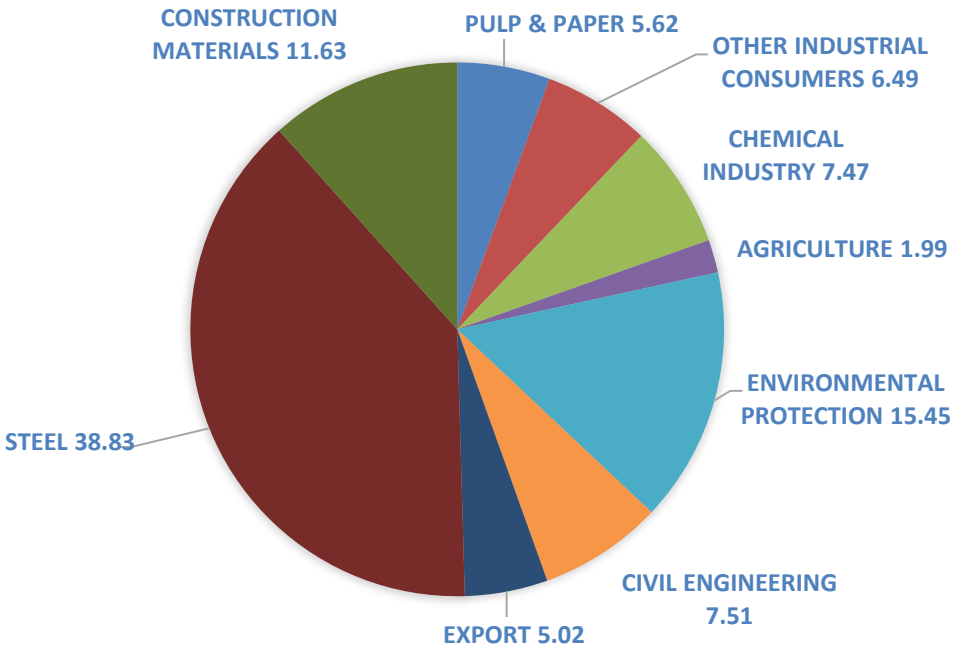


Table 1 - Overview of customer markets and functionality of lime products

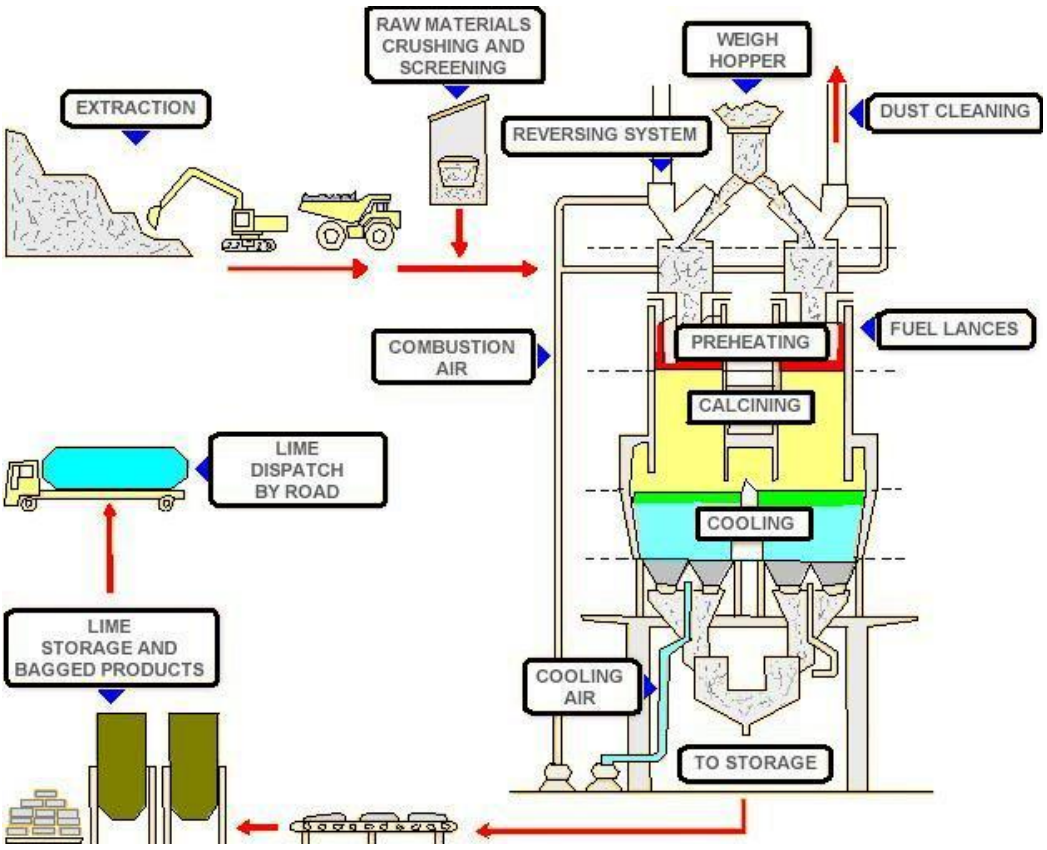
Markets	Functionality of lime products
Steel	• Removing impurities • Enhancing productivity
Environmental protection	• Drinking water treatment : removing heavy metals • Waste water treatment : remove impurities • Flue gas purification
Construction sector	• Lightweight and high insulation construction materials, aggregate, filler and bonding agent

Civil engineering	• Improving stability and load bearing capacity of soil • Improve asphalt durability
Chemical industry	• Feedstock for calcium carbide • Versatile filler in paint, pharmaceuticals and PVC
Agriculture	• Nutrient in Fertilizers • Animal Nutrition • Animal Hygiene: Prevent diseases

3.3 Production process

The feedstock for lime production is calcium carbonate and/or calcium magnesium carbonate, which is extracted from quarries and occasionally from underground mines. Calcium carbonate is used to produce lime while calcium magnesium carbonate is used to produce dolime.

Figure 11 - Lime production process, Source: https://chemistrylimestone.wordpress.com/



The first step of the production is in the quarry where controlled **blasting** is used to break up limestone or chalk rock. The broken rocks are then picked up in the quarry face by excavator and trucks carry the rock into primary crushers in order to reduce the grain size. After the primary crusher,

additional **crushing and screening** takes place until the desired grain size is achieved. Different types of kilns can process different grain sizes. For example, bigger rocks are calcined in shaft kilns and smaller ones go to rotary kilns. In a small share of the plants (<10%), the final product from the crushers is washed. Crushed limestone is also used as an aggregate in the construction sector, for example in asphalt or concrete, or milled to limestone powder.

After the stone preparation, follows the **calcination** step, also referred to as 'lime burning' which is the thermal process of heating limestone. The rock is heated to 800ºC in the preheater and then from 1200ºC to 1800ºC to make lime. The burn temperature and time in the kiln depends on the type of rock that is used as raw material. At the stage of the production, together with lime or dolime is forming, CO_2. When the lime is leaving the kiln is **cooling** with air.

The type of kiln are grouped into two main categories, vertical kilns and horizontal kilns. Vertical kilns are generally more energy efficient with regards to fuel consumption. The most energy efficient kiln is the parallel flow regenerative kiln (PFRK), which is used to produce quicklime as well as dolime. Horizontal rotary kilns typically have a higher production capacity than rotary kiln with pre-heater kilns (PFR), and are capable of burning smaller stone feed sizes than PFR kilns. They are, however, less energy efficient and their energy use is 60% to 120% higher than PFR kilns. They are often used to produce specific products, or in combination with vertical kilns, when the priority is the maximum utilisation of the limestone deposit.

After calcination in the kiln, lime still requires additional processing. Lime **refining** is undertaken to deliver differentiated end products and at ensuring that they fit the quality and property requirements for specific application fields. Additional processing might include crushing or the use of ball mills, roller mills or high-pressure mills. Sometimes after this additional processing lime and dolime may be hydrated by adding water. This **hydration** forms hydrated lime and hydrated dolime respectively. When more water is added then is formed the known "milk of lime".

Finally the lime products are safely wrapped, packaged and stored on site in order to be sent to the customer by road, rail or even boats.

3.4 Energy and CO_2 emissions

The main environmental concerns of lime production are associated with the use of energy and the production of CO_2 emissions. The calcination process is responsible for the most part of energy use and the CO_2 emissions, since the production of lime requires temperatures around 1200ºC and maintaining these temperatures requires a significant amount of heat. Simultaneously, the 68% of total emissions are an inevitable by-product of the calcination process.



The two main reactions that takes place during the calcination process are the followings:

• CaCO3 (solid) + energy → CaO, (solid) + CO_2 (gaseous) (lime)

• CaMg(CO3)2 (solid) + energy → CaMgO2, (solid) + CO_2 (gaseous) (dolime)

In 2010, the average fuel consumption was 4.25 GJ/tonne of quicklime with the theoretical minimum energy required to be 3.18 GJ/t lime and the CO_2 emissions reaching 0.751 t CO_2/ t lime and 0.807 t CO_2 / t dolime. The total direct CO_2 emissions of the European lime industry, based on EUTL, the EU-ETS emissions registry, are around 26 Mt CO_2. So it apparent that the lime industry is a really carbon and energy intensive industry.

Regarding the energy use the production of lime requires heat and electricity, however the electricity consumption is quite low since electricity is mainly used for operating some of the kiln equipment and mechanically crushing the limestone. Electricity consumption is estimated at ±60 kWh/t. On the other hand, heat demands are the one that makes the lime industry such energy intensive. More specific, calcination is the most energy intensive step in the lime production process and although there has been a lot of progress in term of energy efficiency there are some limits that cannot be overcome such as the achievement of temperatures that may reach 1800ºC.[19]

The energy efficiency that is succeed is mainly through the transition to vertical kilns, which are more efficient, since the kiln type plays an important role on the energy consumption. However apart from the kiln type, desired lime, grain size, humidity of the limestone, fuel quality and residual CO_2 content are some other factors that affects the energy efficiency of the production process.

Figure 12 -Parallel flow regenerative kilns (left), shaft kiln (right), Source: EuLA

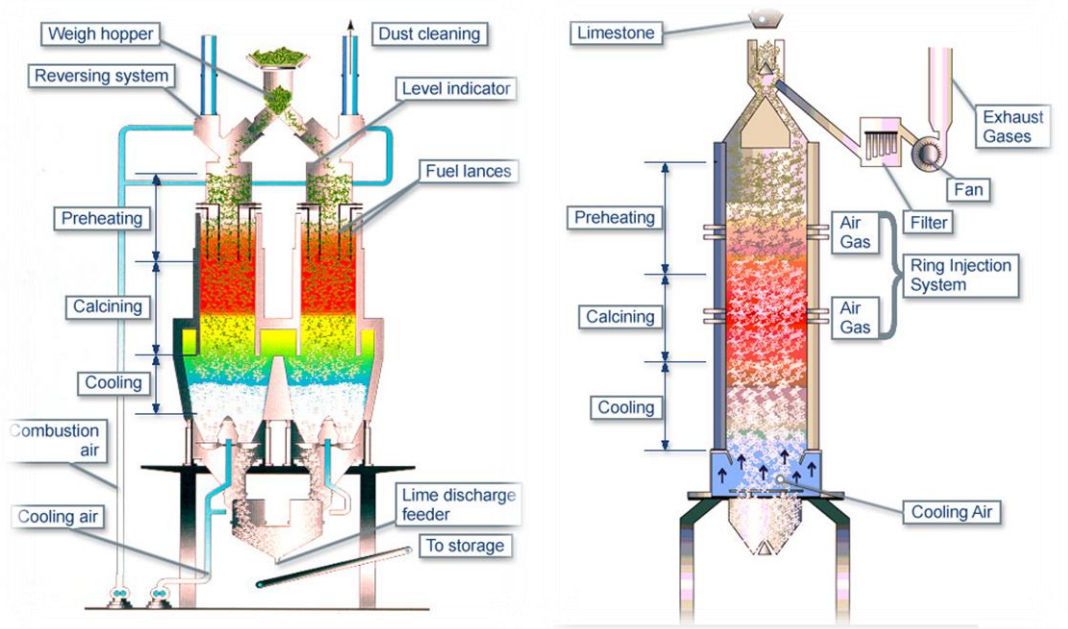


Figure 13 - Rotary kiln, Source: EuLA

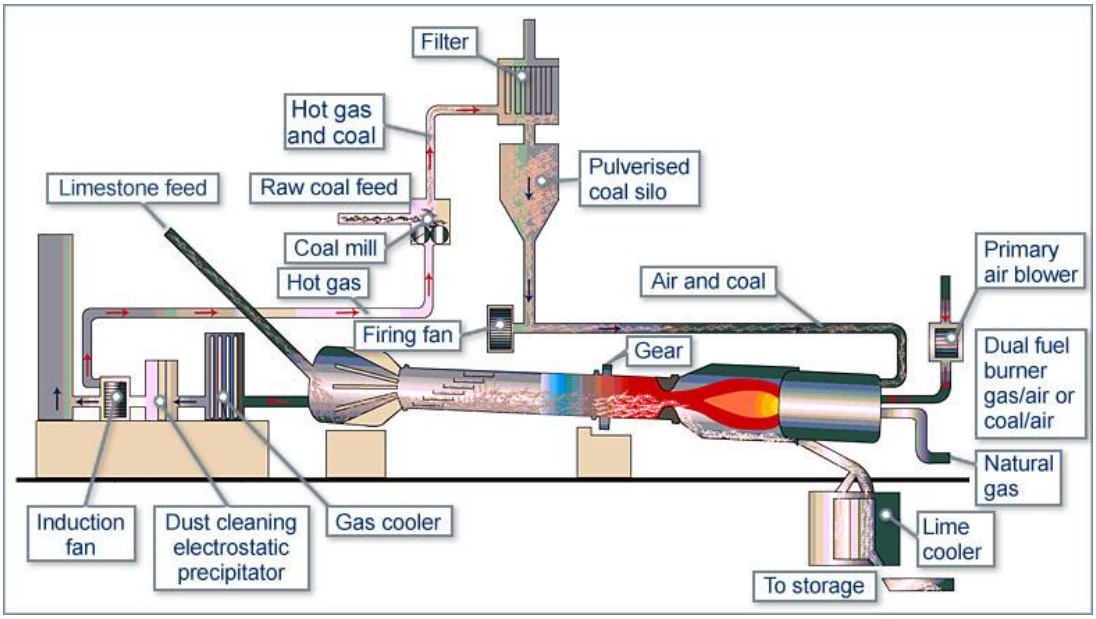
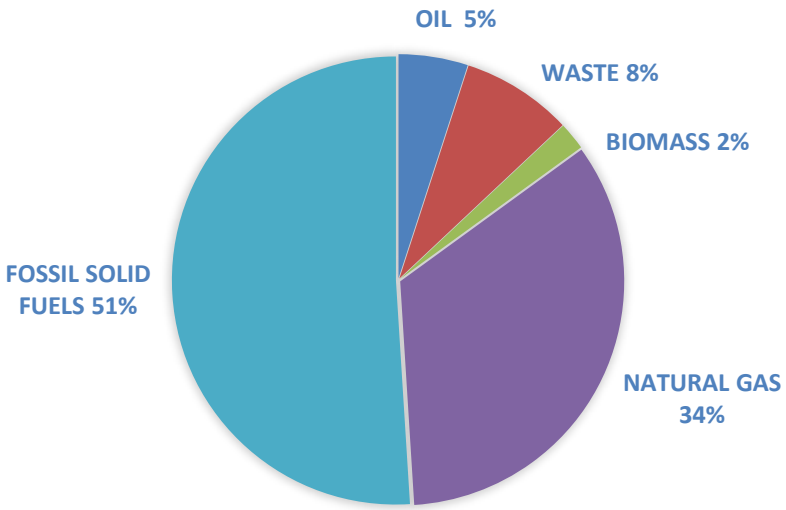


Table 2 -Overview of the minimum and maximum heat consumption per kiln type for quicklime production [15]

Column title	Column title	
Vertical	Parallel flow regenerative kilns (PFRK)	3.2-4.2
	Annular shaft Kilns (ASK)	3.3-4.9
	Mixed Feed Shaft Kilns (MFSK)	3.4-4.7
Horizontal	Long Rotary Kilns (LRK)	6.0-9.2
	Rotary Kilns with preheater (PRK)	5.1-7.8
Other Kilns		3.5-7.0

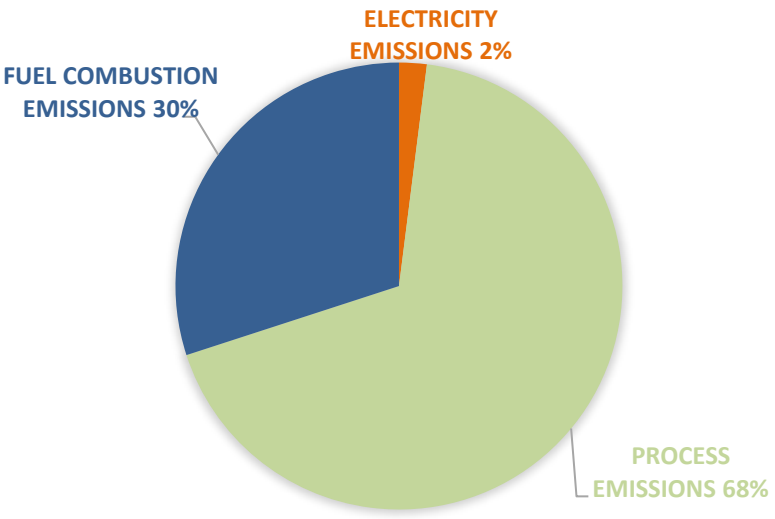
This energy required for heat comes either from fossil fuels (natural gas, fossil solid fuels and oil) or from waste and biomass, however lime production has limited flexibility in use of alternative fuels, due to the impact of energy sources on the purity and cleanness of final products [15].

Figure 14 - Fuel mix, Source: EuLA, 2012



Regarding the CO_2 emissions, during the manufacturing of lime, CO_2 is produced inevitably. The sources of the CO_2 production are two. The first one is the burning of the fuels, mainly the fossil fuels, for the production of heat. These emissions vary depending on the type of lime product manufactured. The second source of emissions is the chemical reaction itself that takes place for the production of lime. These emissions which are the vast majority, are released during the calcination step and are called “process emissions”. Apart from the above direct emissions, there are some small amounts of indirect CO_2 emissions that are produced during the others steps of lime manufacturing, however they are insignificant compared to the combustion emissions and process emissions from calcination.

Figure 15 - Average share of CO_2 emissions in the manufacturing of lime (data of 2010 (EuLA, 2012)).



The total direct CO_2 emissions are around 26 Mt CO_2, according to the EU ETS registry. The specific CO_2 emissions of lime and dolime are presented in the Table 3.

Table 3 -Average CO_2 emissions for lime products (based on data for 2010 (EuLA, 2012)).

	Process emissions (t CO_2 / t lime product)	Combustion emissions (t CO_2 / t lime product)	Electricity emissions (t CO_2 / t lime product)	Total emissions (t CO_2 / t lime product)
Lime	0.751	0.322	0.475	1.092
Dolime	0.807	0.475		1.301

3.5 Measures for reduction of CO_2 emissions

Increasing carbon constraints towards 2050 invite the European lime industry to look for ways to become even more CO_2-efficient, while maintaining its global competitiveness. However, the options for the EU lime industry appear to be limited. One-third of all emissions are originate from energy production through the burning of fuels, and the other two-third are emissions released from the raw material during the calcination step. For the emissions that originate from energy production, the lime industry can apply measures like fuel switch and energy efficiency and as far as for the rest of the emissions which are the 68% of total emissions the only potential solution is the carbon capture. Regarding the emissions related to electricity use although the amounts are small (2% of total CO_2 emissions), some measures for greening-decarbonizing the electricity production could be taken.

The potential measures for the reduction of CO_2 emissions can be divided in four main categories, which will be presented in more details, and are the following:

1. Energy efficiency→ fuel savings

Improving energy efficiency mainly during the calcination step, which is the most energy intensive step, is an important option to reduce energy related emissions. The last decades the European lime industry has made great effort to this direction. It has invested heavily to improve its plants and as a result around 80% of its lime production is produced in vertical kiln which are the most energy efficient kilns at this time. It is estimated that by building new efficient kilns and retrofitting the existing ones the fuel intensity could be reduced by 16% until 2050 and 8% until 2030 [20].

This reduction to fuel intensity can be succeed by tree main methods. The first one is to **switch the horizontal to vertical kilns and in particular to PFRK**, the most energy efficient kiln of the verticals. The only disadvantage is the fact that the vertical kilns cannot process the small particles who are produced during crushing. To overcome this obstacles, at some production plants use vertical kilns to proceed with the bigger particles while the smaller particles are processed in horizontal kilns.

Nevertheless, due to the energy cost and the restriction regarding the emissions, the number of horizontal kilns has decreased and in many cases they have been refurbished although they cannot achieve the same energy efficiency as a new vertical kiln.

The other option is to install **heat exchangers in the existing horizontal kilns** in order to recover some of the heat from the flue gases and preheat with this heat the feed limestone. Vertical kilns already have a preheater zone so this option is applicable only to horizontal kilns and could lead to around 25% fuel savings [20].

Finally, in the future it would also be a big contribution to decarbonisation of the industry if all the **vertical kilns to be switched to PRFKs**.This replacement can be challenging, as each kiln type has its specific applicability (different feeds - particle size), different products, and different optimal operation conditions. So, further innovation could increase the applicability of PFRKs enabling them to handle smaller particles and, thus, making them more resource efficient.

Apart from the above measures, **energy heat recovery from the waste heat** from the kilns but also during the exothermal reaction of hydration, could be used in drying limestone or in the milling process or in heating buildings and producing electricity. The economical attractiveness, taking into account the transportation cost due to the long distances from industrial areas, is something that has to be considered.

As far as concerns the electricity savings the best way is the reduction of power consumption. This could be happened through the **efficiency of motor systems** which could have a potential saving of 10%. Moreover, **optimizing cooling** could lead to a reduced consumption of cooling air and **optimizing grinding** could lead to higher efficiency gains.

2. Low carbon sources → fuel switch

The stage of calcination is the most energy intensive. The use of fuels is mandatory for the production of the required heat and the fuels that are used usually is natural gas and fuel oil. The increasing efforts to reduce fossil fuel use and carbon dioxide has led to their substitution to renewable alternatives. The main alternatives are the wood powder firing and biomass gasification but also methanol, turpentine and tall oil may also be available for burning in lime kilns. These work well as support fuel, but they cannot normally cover the lime kiln's fuel requirements. In addition lignin could also be used as fuel in lime production and finally the last decade the use of hydrogen is a potential and promising option.



Table 4 -Properties of the Studied Alternative Fuels Compared with the Most Commonly Used Fossil Fuels [21]

Fuel	Lower Heating Value (MJ/kg)	Adiabatic Flame Temperature (°C)	Contaminants
Hydrogen	120	2210	No
Producer gas	6-30	1870	Some
Torrefied biomass	20-30	1840	Substantial
Lignin	17-26	1980	No
Wood	12-19	1950	Substantial
Natural Gas	50	2050	No
Oil	41	2210	Some

Towards the fuel switching, another option is the use of waste as fuel source. However, the quality of these waste fuels is important in lime manufacturing since the use of waste has an effect on the lime quality, such as the limitation of the usage of the lime. Also not all types of kiln can process all types of waste. In any case, the use of waste fuels is also cost effective in relation to transport costs and unit prices of these fuels [15]. The EU Member States subject the use of waste fuels to rather different legal requirements. Requirements are imposed on the characteristics of wastes and on a number of substances which are contained in waste materials.

Another potential solution for the decarbonisation of lime production is the use of renewable energy and basically solar heat. In the future, high-temperature Central Receiver Systems (CRS) with pressurised air could reach temperatures up to 1000 °C [19]. However this is applicable only for Southern Europe and it is still in an experimental phase, so further research is required.

Finally, hydrogen production using alkaline electrolysis is a developing technology.The profitability of the hydrogen concept is highly dependent on the price of electricity, which should be remarkably lower than current levels but it can be expected that the price will decrease in the near future as power-to-gas processes become more common.

Many factors have to be taken into account when selecting the right fuel source, for example biofuels



effect the operation of the lime kiln, lime quality, temperature profile, capacity, and emissions. Also the attractiveness of each of the concepts is dependent on local conditions and especially the prices of fossil fuels and electricity.

3. CCS-CCU

Almost the 70% of the total CO_2 emission of the lime industry are produced when the reaction where the limestone is heated takes place, and even if energy efficiency is succeeded and the fuel mix is optimised, still there will be remarkable emissions, so it is obvious that the major share of the emissions are not impacted by any of these measures. The only solution that could be effective in the CO_2 emissions reduction is the CCS & CCU which considered as end of pipe solution. However, although capturing carbon is the answer to the problem its implementation in term of cost will be challenging. A study that was made by Netherlands Organization for Applied Scientific Research regarding the cost of capturing in 2012, calculated that the cost was around 94€/tonne of avoided CO_2 even with the use of lowest electricity price. This would double the production cost which not feasible for the industries. Solutions such as the utilization of waste heat or further future innovations could reduce the costs and make the carbon capturing an attractive potential.

The options regarding the captured CO_2 emissions are two, the storage and the utilization. In the case of storage there must be considered the fact that because the lime plants most of the times are not close to industrial zones, there is a cost the transportation to a geographically suitable location. Also additional cost that could significantly rise the costs is any additional piping infrastructure. Finally, last but not least apart from the fact that there are limited storage locations, public and regulatory acceptance must be gained in first place. Regarding the CCU, would be a better solution to use the captured CO_2 than to store it. This way storage costs could be saved and although the lime industry does not use CO_2 itself could benefit from others using it. This way the CO_2 could have a financial value. To this direction a lot of research is focusing on new uses of CO_2 such as the use in the production of fuels/hydrocarbons, transforming CO_2 into inert carbonates in constructions etc. However all this applications are at research stage. Consequently, as a solution the CCU is preferred but still needs to be scaled up to industrial application.

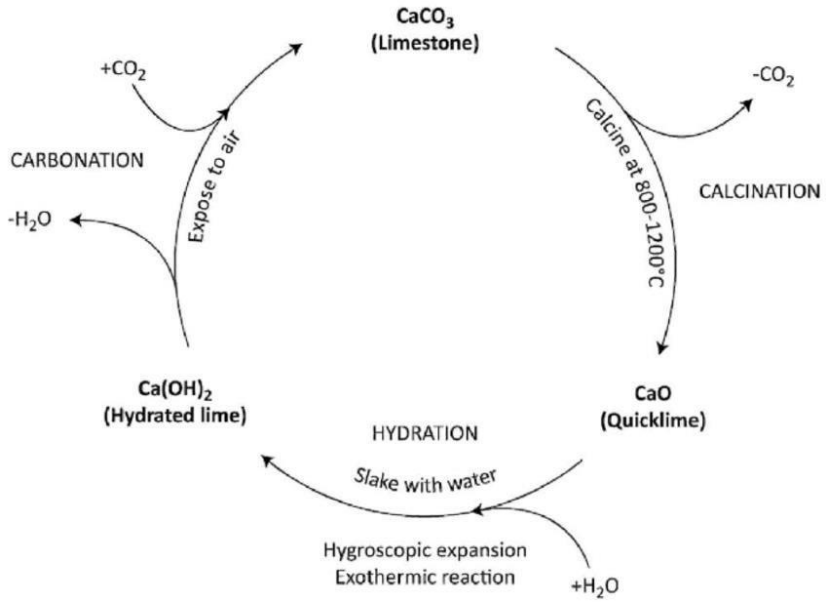
Taking into account all the above, at this time, CCS & CCU is not an economically viable solution since the costs are high in comparison with the production costs of lime, however since it is the only option to drastic reduce the process emissions, given the right technological development, economic support and infrastructural requirements the lime industry would be willing to embrace this technology.



4. Carbonation

Carbonation is the natural effect associated with the use of lime and it can be described as the reverse reaction of lime production. During the lifetime of products that contains lime, CO_2 from the atmosphere is captured forming limestone and by this way the cycle of lime is closing.

Figure 16 - Lime Cycle [22]



The carbonation is taking place after the hydration step, which could be during the manufacturing step or naturally by atmospheric wetting. So, if there is a good access of lime material to the atmospheric CO_2 over time CaCo3 is forming again. The rate of the carbonation plays an important role and depends on the application because in some applications the main carbonation takes place within five years well in others it takes longer. By the effects of carbonation it is estimated that around 2% of CO_2 emissions that produced in the calcination step could be absorbed.

Finally an industrial example of the carbonation mechanism is the precipitated calcium carbonate (PCC), which is an innovative, high purity lime product obtained by reacting lime with CO_2 and it is used as a filler in many applications, like papers, plastics, rubbers, paints and drugs.

3.6 Challenges and risk management

The EU lime industry as the whole the European industry has many challenges to face. However the lime industry's challenges are mainly financial challenges. The lime industry as a carbon intensive sector has made big efforts to lower its emissions substantially, mainly by modernising plants and adjusting the fuel mix.

However, the two third of the emissions are process emission and are producing from the material

itself, when the reaction of calcination is taking place. This leads to inevitable CO_2 emissions which means that high carbon costs reduce the competitiveness of lime industry. These high carbon costs has two impacts. The first one the reduction of EU demand of lime products due to the fact that the lime industry is at the beginning of the value chain, suppling other industrial sectors who might relocate their production in order to avoid the carbon cost. The other impact is that due to the high carbon intensity of lime production processes, carbon pricing has as a result higher costs for lime production, leading to high lime prices and harming its competitiveness. So, although the transportation of lime outside EU is costly when carbon costs increase even more, it pays off to import lime from even larger distances. In particular, countries that are bordering Europe have low energy and transport cost and also they do not pay carbon costs which makes them large competitors for the EU lime industry.

Apart from the carbon cost which has negative impact on the competitiveness, there are also the costs related to the measurements taken due to regulatory restrictions and the fact that the industry wants to reduce the CO_2 emissions in order to avoid the carbon costs and maintain its competitiveness. To this direction although there are several abatement solutions, a wide scale implementation is currently inhibited due to high investment costs but also due to the long payback periods. So, although the EU lime industry want to invest in order to remain competitive it not financially viable.

In order to continue EU lime industry to play an important role, it is absolutely vital, EU to make a long term policy certainty and this way support the maintenance and competitiveness of its plants.

The lime industry needs industry regulatory predictability and stability. Toward this direction and due to absence of a global climate agreement, compensation for climate costs is needed for lime industry in case of carbon leakage, but also organized actions for the creation of a global level playing field for climate policies. However climate policies are directly related to energy policies and energy markets, therefore energy policy should consider integrating energy requirements in international negotiations, guarantee a diverse and more competitive energy supply in Europe and of course eliminate differences of energy prices within Europe as a consequence of national differences in energy taxation, if maintaining the competitiveness is the goal.

In addition, European Commission should focus on innovation, stimulating research, reducing barriers for subsidies, and by developing adequate financing systems for the early adoption of energy efficient and low carbon techniques. These systems could be financed by using part of the revenues from ETS to provide cheaper loans for low carbon investments in installations falling under the EU ETS [19].



Accordingly, CCS-CCU which is the most important option of lime industry to eliminate the CO_2 emissions, needs to be developed and deployed. Supporting this solution, European Commission should consider investigating the possibility of providing public infrastructure for transporting and storing CO_2. This enables EU lime industry to quickly take CCS/CCU on board once economically viable.

Finally, the acceptance and recognition of carbonation of lime products as a technique of CO_2 emissions would be beneficial for the lime industry.

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RE4INDUSTRY

100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

D3.1 - EIIs Sector Status in Europe

Ceramics industry

Author: Alessandro Carmona

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Abbreviations

Abbreviation	Definition
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
EU	European Union
ETS	Emissions Trading System
IEA	International Energy Agency
MAT	Microwave assist technology
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
TAS	Technological advancement status
TCKI	Technical Center for the Ceramic Industry Foundation in The Netherlands
SMEs	Small and Medium Enterprises

1 Introduction and objectives

The **EU ceramics industry** is a world leader in producing uniquely designed high quality ceramic products such as tiles, bricks, sanitary ware, or vitreous clay pipes. Most manufacturers are innovative small and medium-sized enterprises (SMEs). Even though the industry was hit hard by the economic crisis, there are signs of recovery. The ceramics sector provides over 338 thousand jobs and accounts for €27.8 billion in production value. EU manufacturers are mainly represented by SMEs that react quickly to changing demand and new opportunities. The use of automation and environmental technologies are widespread. Clusters fuel innovation and enhance competitiveness.

Innovations include the industry's specialisation in value added products, access to new markets in emerging economies, and its ability to offer just-in-time and just-to-market service. The sector is increasing its research and development in technical ceramics, smart materials, the use of lasers, process automation, and labelling. Products with high weight and low price (bricks, roof tiles) have local or regional markets, whereas tableware and tiles are traded over long distances. Around 30% of the output of tableware and tiles is exported outside the EU. The USA is the EU's biggest export market, followed by Switzerland, Russia, and Japan. 70% of all imports are from China, followed by the USA, and Thailand. Issues concern counterfeiting and access to non-EU markets. Import tariffs and other trade barriers are creating difficulties for EU companies that want to export outside the EU. The EU interest test ensures that the costs resulting from anti-dumping duties do not negatively impact on the industry's competitiveness. Access to raw materials is of key importance, especially for the refractories sub sector where certain countries control up to 90% of the raw materials (magnesia, bauxite).

Ceramics production processes are energy intensive with the bricks and roof tiles sector being the biggest energy consumers. The industry has halved its energy consumption over the last 25 years as a result of a switch in fuel usage. Dust and gaseous emissions arise during the firing or spray drying of ceramics and may be derived from the raw materials and/or the fuels used. Heavy metals can be emitted due to substances used in decoration or the use of heavy oil. Some of the waste from the production process can be recycled back to the kiln. The rest is sent for external recycling (road construction) or disposal (landfill). Some producers are beginning to bring in waste for recycling.

Following this introduction, Chapter 2 gives a general overview of the ceramics sector and its importance for the European and global economy. Chapter 2 englobes the main industrial activities in the ceramics industry, concerning production as well as the highest overall energy consumption. The report provides information on the current usage and importance, main production processes, energy and GHG emission profile, as well as potential alternatives for cleaner production processes for mitigating their climate impact. Each of the Chapters 3 to 6 focuses on a specific glass subsector or product giving a brief description of these sub-sectors of the European ceramics industry.



2 Ceramics

From a chemical point of view, ceramics are non-metallic inorganic solids. For many, ceramics mean things like tableware, roof tiles, flowerpots, coffee cups, bricks in a fireplace, or a pizza oven or tiles on a kitchen wall (Figure 1). These products are known in the industry as traditional ceramics. Beyond these everyday household items, there exists various cases where ceramics are used. Refractories as a part of ceramics are used as a refractory material due to their resistance to heat, mechanical stress or chemicals. Since they keep their shape and strength at high temperatures, they are used in all extreme-temperature industrial processes, primary in metallurgical process but also cement, glass, energy chemical processes and more. Technical ceramics are considered to be one of the most efficient materials. They are applied in many industries and include established products, such as insulators, engine parts, catalyst carries, bone replacement, filters, among others [1].

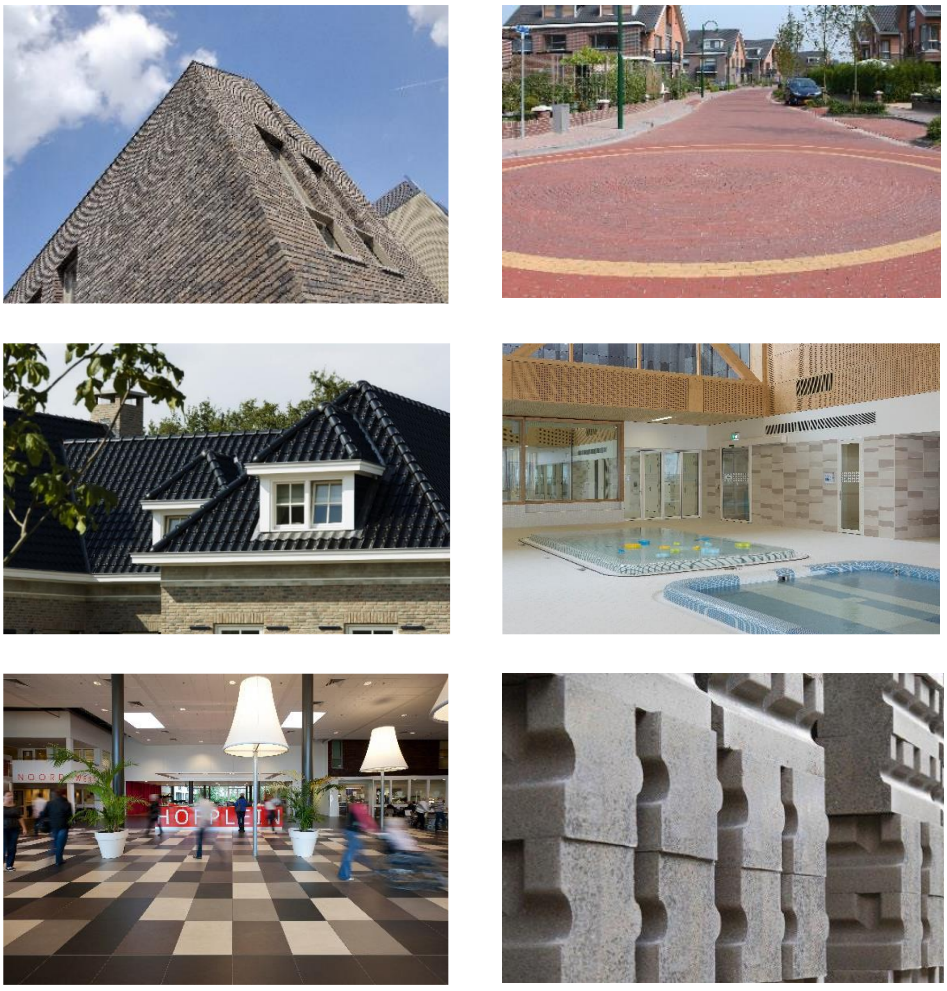


Figure 1 – Bricks, roof, wall, floor tiles and refractory products [2].

Table 1 – Number of installations producing ceramic products per country [3].

Country	No. of installations	Country	No. of installations
Austria	33	Italy	35
Belgium	34	Latvia	6
Bulgaria	21	Lithuania	8
Cyprus	8	Netherlands	42
Czech Republic	64	Norway	3
Denmark	25	Poland	50
Estonia	2	Portugal	70
Finland	4	Romania	32
France	51	Slovakia	11
Germany	138	Slovenia	9
Greece	45	Spain	287
Hungary	43	Sweden	5
Ireland	3	United Kingdom	70

2.1 Main ceramics products

2.1.1 Bricks

Brick products are produced in large quantities and are mostly used in the construction sector. The main subtypes for bricks are facing bricks, paving bricks and inner wall bricks. Facing bricks are commonly used for the external walls of domestic and commercial properties. They are used for surfaces that are exposed to weather conditions and the appearance of such surfaces is important. Inner wall bricks on the other hand are used for the part of the building structure facing inwards. Paving bricks are used to be laid flat on the ground and they are designed specifically to last to all weather conditions [2].

2.1.2 Roof tiles

Roof tiles are designed to withstand harsh weather conditions and are designed specifically to keep out rain [2].

2.1.3 Wall and floor tiles

A ceramic tile is a thin and usually square or rectangular object made from clay and other inorganic materials that is generally used as covering for floors or walls. The tile sides range from a few



centimetres to 60 - 100 cm sides. Their thickness can vary from around 5 mm to 25 mm. Maintenance and renovation is an important aspect of ceramic tile usage [2].

2.1.4 Refractory products

Refractory bricks are used for inner linings of ovens, for example in the steel or glass industry. Due to the high temperatures in such ovens, these bricks must be able to withstand extremely high temperatures. This is already indicated by the high temperatures to fire this product (around 1700 °C). The main users of these refractory products are industrial installations using high temperature processes, such as petrochemical industry, non-ferro producers, and users of combustion installations [2].

2.2 Ceramic associations

Table 2 shows the different subsectors within the EU ceramics industry and the association representing them.

Table 2 – Ceramics sectors and their respective associations. Source1.

Subsector	Association
Bricks and roof tiles 	**TBE-Tiles & Bricks Europe** Tiles & Bricks Europe (TBE) was founded in 1952 in Zürich and registered as an international non-profit organisation (AISBL) under Belgian law in 2008. TBE represents industry associations and companies from 22 EU Member States plus Norway, Russia and Switzerland. The association promotes interests of clay bricks and roof tiles industry in Europe. It provides a forum for its members to exchange information on technical development, sustainable construction, climate change, resource efficiency and other emerging issues. It represents over 700 companies, which **employ around 50,000 people** and generate a **production value of around €5.5 billion.** In Europe there are around 1,300 production sites located near quarries which provide local jobs and keep transport emissions low.
Wall and floor tiles 	**CET-European ceramic tile manufacturers federation** Wall and floor ceramic tiles constitute the biggest sector in terms of turnover among European ceramic industries with total **sales in 2009 estimated around € 9 billion.** Although Italy and Spain are by far the two biggest producers in the EU, significant production also exists in Poland, Portugal, Germany, France, Bulgaria,

[1] https://cerameunie.eu/ (accessed on April 2022)

	the UK, Romania, the Netherlands, Czech Republic and Hungary. One third of the production in ceramic tiles is exported outside of the EU, resulting in a largely positive trade balance with exports representing in value around four times the EU imports in ceramic tiles. At international level, CET holds the secretariat of the World Ceramic Tiles Forum.
Table and ornamental ware 	**FEPF-European federation of ceramic table and ornamentalware** The European Federation of Ceramic Table- and Ornamentalware (FEPF) is a member association of Cerame-Unie. It was founded in 1959 and its secretariat is based in Brussels. Its membership currently covers producers in France, Germany, Italy, United Kingdom, Spain, Portugal, Poland, Romania, Croatia and Hungary. FEPF developed contacts with the industry in other countries e.g. in Czech Republic as well as in countries where no national associations exist (e.g. Austria, Bulgaria, Lithuania and Slovenia.) The sector **employs 25,000 skilled people**.
Sanitaryware 	**FECS-European sanitaryware producers federation** Established in Geneva in 1954, the European Sanitaryware Producers Federation (FECS) promotes the interests of the ceramic sanitaryware industry in Europe. Today it represents seven national trade associations and ten companies from 15 countries (European Union, Turkey and Switzerland). FECS directly **employs approximately 22,000 people** and has an annual **turnover of € 4.5 billion**.
Refractories 	**PRE-European refractories producers' federation** The European Refractories Producers Federation (PRE) is the representative organization of the European refractory industry, founded in 1953. PRE unites members from 16 countries, from Sweden to Italy, from the UK to Poland. Four multi-national companies, namely Calderys, Magnesita, Refratechnik and Vesuvius, are also direct members. PRE represents an annual **turnover of € 3.5 billion** and **employs nearly 20,000 people**.
Technical ceramics 	**EUTECER-European technical ceramics federation** The European Technical Ceramics Federation (EuTeCer) represents the technical ceramics industry in Europe, with members in the UK, France, Italy, Germany, Romania and Turkey.
Clay pipes	**FEUGRES-European federation of clay pipe producers** The European Vitrified Clay Pipe Federation (FEUGRES) represents the vitrified clay pipe industry in Europe and was founded in 1957 in Switzerland. FEUGRES

	has members from Belgium, Germany, the United Kingdom, Italy, the Netherlands, Austria and Switzerland.
Expanded clay	**EXCA-European expanded clay association** European Expanded Clay Association (EXCA) was established in 2007 as an asbl, a non-profit making organisation, under Belgian law. EXCA represents and promotes the interests of the European producers of expanded clay. Today, 12 companies operating some 20 plants in Belgium, Czech Republic, Denmark, Finland, Germany, Italy, Norway, Poland, Portugal, Sweden and United Kingdom are members. Through its members, EXCA represents more than 90% of the production in Europe. Visit the EXCA website to find out more.

2.3 Overview of the European Ceramics sector

The European ceramic industry today employs over 200,000 people in the EU-27 with around 80% of them in SMEs. World-leading companies are headquartered in the EU and the industry develops highly-skilled and trained employees (Figure 2).

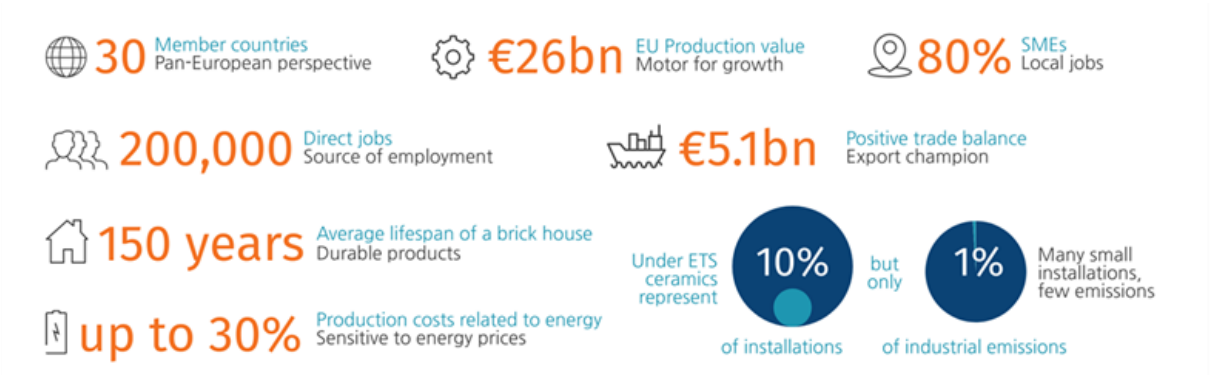


Figure 2 – Facts of the European Ceramics Sector.

Ceramic wall and floor tiles accounted for the largest share of the production value of ceramics in Europe in 2018, at 31 percent[2]. Bricks and roof tiles made of ceramics were the second largest European ceramics end-use segment, accounting for a 20 percent share of the industry's production value that year (Figure 3).

[2] https://www.statista.com/statistics/1248963/distribution-of-european-ceramics-production-value-by-end-use/ (accessed on April 2022)

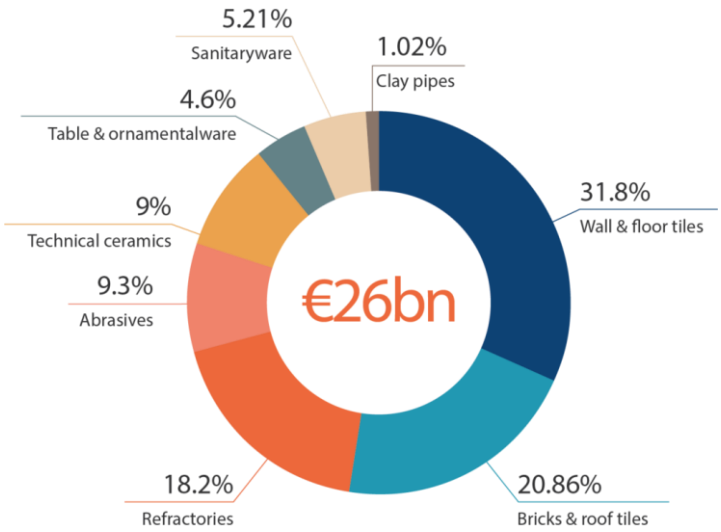


Figure 3 – European Ceramics production value3.

2.4 Ceramics main applications

With its wide range of applications, from construction to consumer goods, industrial processes and cutting-edge technologies, the ceramics industry is consistently developing innovative and high-value solutions that improve our quality of life and facilitate vital progress in downstream sectors (Figure 4)[4].

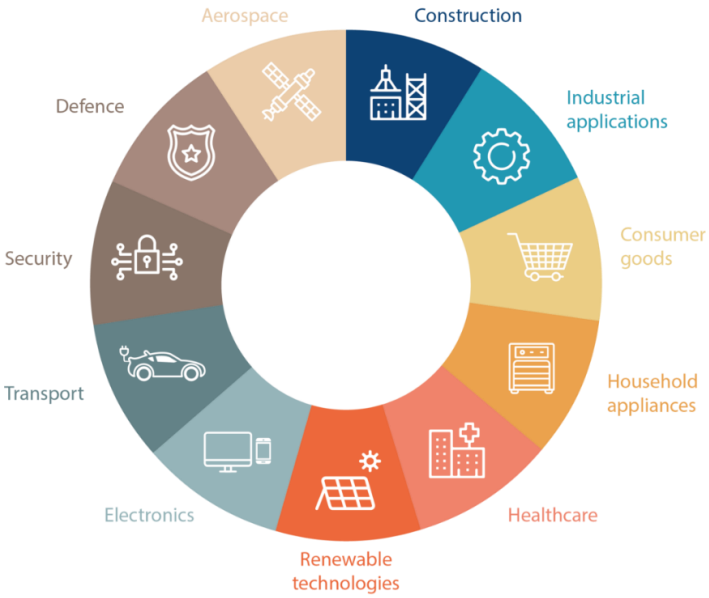


Figure 4 – European Ceramics main applications5.

[3] https://cerameunie.eu/ (accessed on April 2022)
[4] https://cerameunie.eu/ceramic-industry/applications/ (accessed on April 2022)
[5] https://cerameunie.eu/ (accessed on April 2022)

2.4.1 Construction and housing

Ceramic-based building materials have an average service life of over a century and boast excellent resource efficiency at all lifecycle stages. Their durability supports the optimisation of a raw material with many advantages for the construction and housing sectors. The unique properties of ceramics - enhancing energy efficiency and thermal comfort in all climates, resilience to corrosion and versatility - ensure that ceramics will continue to play a fundamental role in the construction and housing sectors.

Bricks and roof tiles

The production of bricks and roof tiles is one of the most well-known applications of ceramics. Bricks and roof tiles have been used for centuries because of their proven ability to protect homes from the elements. As an inert product made from natural materials, ceramic tiles and bricks are nontoxic, do not emit volate organic compounds (VOCs) and provide a healthy indoor climate. Ideal for sustainable housing, bricks are highly resistant to fire and provide insulation from sound and vibrations, electricity, electrostatic and ionising radiation.

Wall and floor tiles

Moulded in an endless number of designs and formats, ceramic wall and floor tiles build on 2,000 years of tradition to provide durability, aesthetics and technical solutions in private and public buildings. No longer just a decorative feature inside homes, wall and floor tiles have become indispensable in the provision of hygiene. A new generation of coatings gives tiles the ability to destroy organic matter that settles on their surface and encourages water to slide off, while antibacterial tiles with light-activated antibacterial surface coatings kill hospital bacteria. Ceramic tiles are highly innovative: new forms of ceramic sheeting include fibre-reinforced ceramics, ceramic composites containing conductive layers for heating systems, inner porous layers for thermal and acoustic insulation, and strong, lightweight thin tiles that minimise the tiles' environmental impact.

Vitrified clay drainage pipes

An essential part of municipal infrastructure, vitrified clay pipes transport wastewater safely and effectively away from buildings and roads and on to treatment plants. The raw material used in clay pipe production is a completely natural, inert resource and is available in virtually unlimited reserves. Vitrified clay remains inert even when subjected to extreme temperatures or chemical attack and when it is eventually taken out of service, it is completely recyclable. Currently up to 40% of the raw material used in vitrified clay pipe production can come from recycled clay products.



Sanitaryware

Favoured by architects and interior designers, ceramic washbasins, toilets, bidets and shower trays are found in homes and buildings the over world. Increasingly innovative designs in the sanitaryware sector mean that ceramics can offer a huge range of products covering nearly every kind of application requested by the market. Ceramics' light resistance ensures that ceramic sanitaryware does not fade or age, while the glazing process delivers smooth, easy cleaning surfaces and optimal hygienic characteristics. Ceramic sanitaryware has made a huge contribution to the reduction of disease in general and a dramatic reduction in the water consumption of household appliances.

Expanded clay

Expanded clay is a well-proven, high quality, efficient and durable lightweight aggregate suitable for a wide range of applications in the construction sector. Expanded clay is various sized granules, each with a hard ceramic shell that surrounds a honeycomb core. It is a sustainable construction material packed with properties that improve the economic, social and environmental performance of a building or infrastructure over its whole lifetime. Expanded clay combines low density with high strength. In addition, the aggregate holds many other important characteristics, and it can be described as an "all-in-one" product, providing a huge range of properties vital for sustainable construction.

2.4.2 Consumer goods

Ubiquitous in consumer goods, ceramics present a natural, affordable and long-lasting choice of raw materials whose transformation into an array of consumer goods is achieved with minimal environmental impact. The complex chemistry of many ceramics facilitates their use at high temperatures and their robustness in coping with high speeds during manufacturing processes. Unique properties such as high resistance to abrasion, chemical inertness and dimensional stability ensure that ceramics today have the longer life and lower maintenance costs required to maintain the pace of technological advances.

Tableware and ornamentalware

Ceramic table and ornamentalware, whether made of porcelain, stoneware or earthenware, have long been part of our culinary rituals. Fired in kilns using abundant natural resources like clay and sand to create these stone-like substances, ceramics have had an astonishing legacy throughout history, providing civilisation with as many varieties as there are cultures and cuisines. From the vases, utensils and carrying vessels of yesteryear to the dinnerware, fine chinaware and hotel porcelain of today, the natural longevity of ceramics ensures that they will continue to evolve with



the times and remain the first choice for serving food.

Household appliances

The ability of ceramics to withstand very high temperatures makes them ideal materials for cooking and heating appliances. Ceramic-coated frying pans are a common replacement for other, more controversial non-stick coatings. Ceramic water filters provide safe drinking water to millions of people all over the world. These filters are relied upon in the most demanding situations like war zones and natural disasters.

2.4.3 Industrial applications

The ability of ceramics to withstand extremely high temperatures, as well as their durability, strength and non-corrosive properties make them essential for a number of specific applications required in metallurgical processes, glass production and many other key processes across all industries. Gears used for steelmaking or quarrying often include advanced ceramics because their wear, corrosion and thermal resistance offer significantly longer life compared to conventional metal gear.

Abrasives

Abrasives comprise a small but indispensable industry. Much of the complex machinery required by industries, as well as the smooth finishes in countless applications, from diamonds, watches and furniture to kitchen appliances and aircraft, is ground, cut, drilled or polished with abrasives. The European abrasives industry significantly impacts productivity in other industrial and services sectors, including steel, metal processing, automobile manufacturing, space, glass, construction, stone processing, shipbuilding, clean-tech, machine-building, wood processing and defence industries.

Refractories

Refractories are essential for all high-temperature industrial processes. They play the triple role of providing mechanical strength, protection against corrosion and thermal insulation. The lining of every single reactor, transport vessel or kiln uses a wide range of refractory products including bricks, monolithics and high-temperature insulation wool. The functionalities of technical ceramics and refractories meet critical needs in steel, aluminium, cement, glass, the chemical industry and environmental applications as well as for energy generation, all of which create some of the most corrosive high-temperature environments in industry today. They take advantage of the improved energy efficiency, productivity and metal quality that refractories and technical ceramics bring to handling smelting, melting and molten materials processes.



Porcelain enamel

Porcelain enamel, also known as vitreous enamel, is a high-tech coating that shares many characteristics with ceramics. Like ceramic glaze, porcelain enamel is an amorphous, inorganic, non-metallic solid, fired on a substrate at high temperatures. Ceramic glazes are used to coat clay while porcelain enamel is used to coat metal products such as hot water tanks, appliances (especially cookers), pots, pans and sanitaryware. Porcelain enamel can be produced in a complete color palette, with a continuous variation between glossy and matt, between rough and smooth. Moreover, the enamel coating is unaffected by exposure to weather and light. Some key functional properties are its hygienic nature, superior mechanical resistance to abrasions and scratches and chemical resistance to acid, alkali and water.

2.4.4 High-tech innovation

Ceramics have become indispensable in cutting-edge technologies. Advanced technical ceramics have unique mechanical, electrical, thermal and biochemical properties that enable their use in a variety of applications in the automotive industry, electronics, medical technology, energy and environment and in general equipment and mechanical engineering.

Healthcare

Medical, laboratory and pharmaceutical instruments as well as ceramic components are used extensively in healthcare, in blanks for the production of crowns, bridges and implants in dentistry and also in implantable medical devices such as pacemakers or hip replacements. Due to their biocompatibility, wear resistance, chemical and corrosion resistance, low allergenic potential, ceramic biomedical implants are the optimum solution for problems arising from disease, infections and other complications, and continue to deliver improved performance in healthcare.

Electronics

Ceramic substrates, circuit carriers, core materials and many other components are in use throughout the electronics industry. Ceramic heat-sinks provide the perfect climate for high-power electronics, while ceramics' electrical insulation properties allow them to be used in microchips, circuit boards and circuit breaker technology. Combined with other unique properties, ceramic components are found in a wide range of demanding applications that ensure reliable functioning in aerospace technology, the automotive industry and optoelectronics.

Security and transport

Applications of technical ceramics in security and defence include bulletproof vests and infrared night



vision devices. The high thermal insulation and wear-resistant properties of ceramics explain their use in jet engine turbine blades, disc brakes and bearing components. Contributing to safety and reliability, technical ceramics are found in a vast range of applications.

Renewable technologies

Many functions in renewable technologies require high-quality products that can only be manufactured with high-quality abrasives, refractories and technical ceramics. The production of the high-purity glass required for solar panels is one example, refractory products used for manufacturing silicon wafers (the semiconductor in crystalline silicon solar panels) is another. Ceramic-based products are also widely used in wind turbines and other solar panel components, such as anti-friction bearings, heat sinks, fuel cells, tensiometers and insulation rings.

2.5 Production process

Ceramics are made from mined materials (such as clay, bauxite, magnesite), water, fire and air. The main raw material is clay, a resource available in large quantities. Technical ceramics and refractories are made from a huge variety of raw materials such as aluminium oxide (more commonly known as alumina), magnesia, graphite, corundum and silicon carbide [1].

Ceramics are generally made by taking raw materials, adding additives, powders, and water, then shaping them into forms, which are dried and fired in a high temperature oven known as kiln (Figure 5).

This process creates commercial products that are diverse in size, shape, detail, complexity, material composition, structure and cost. Ceramic products that use naturally occurring rocks and minerals as a starting material must undergo special processing in order to control purity, particle size and particle distribution.

Chemically prepared powders are also used as starting materials for some products. These synthetic materials can be controlled to produce granules or powders with precise chemical compositions and particle size. The next step is to form the ceramic particles into a desired shape. This is accomplished by the addition of water, steam, or additives such as binders, followed by a shape-forming process.



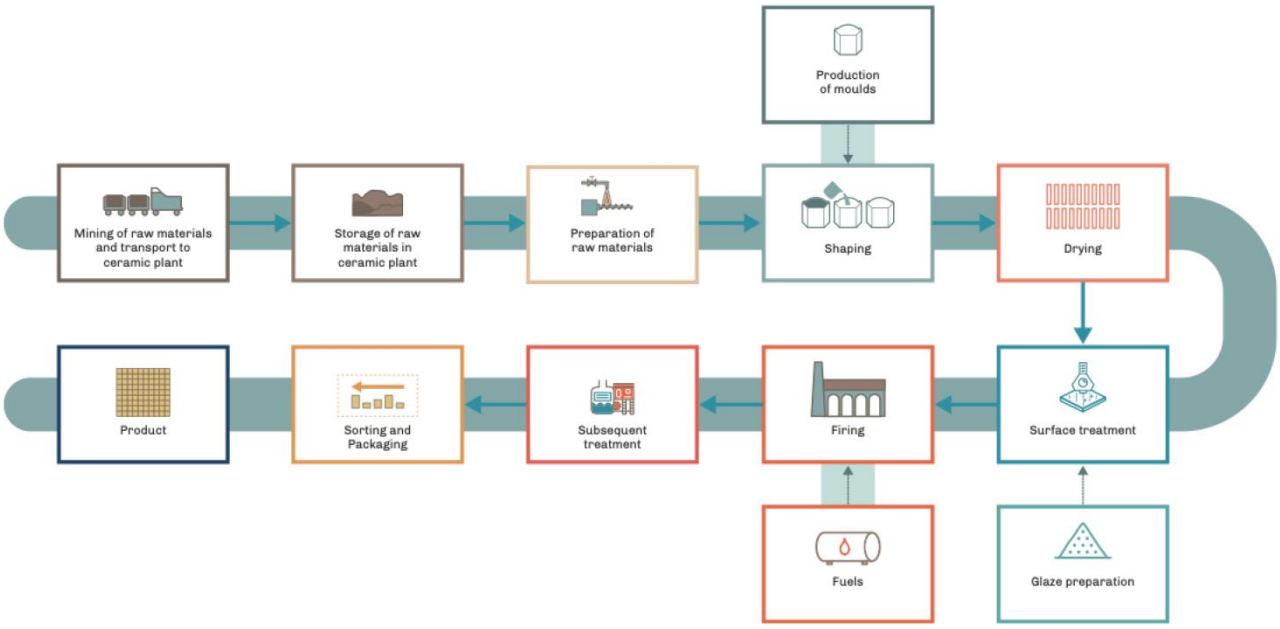


Figure 5 – Simplified diagram of the stages in the manufacture of ceramics products (the process varies depending on the ceramic subsector). Source6.

Some of the most common forming methods for ceramics include pressing, slip casting, extrusion, tape casting and injection moulding. More recently, there is a growing use of ceramic 3-D printing in technical ceramics applications with benefits not only in terms of functionalities but also in terms of resource efficiency.

The products are dried and heated to produce a rigid, finished product. Some ceramic products such as electrical insulators, dinnerware and tiles may undergo a glazing process. Ceramics for advanced applications may undergo a machining and a polishing step to meet specific engineering design criteria.

2.6 Energy consumption and GHG emissions

Natural gas is the main energy source in ceramic industry. The consumption of natural gas in kilns in the process of firing and drying reaches approximately 85% of the whole of energy consumption in the manufacturing process. The consumption differs for different final product but the structure mainly based on natural gas for firing and drying is similar for every type of final product. Electrical energy is used mainly for comminution, mixing and forming. It stands for approximately 15% of energy consumption in sector. In some cases, electrical energy can be used in drying and firing

[6] http://www.tiles-bricks.eu/industry (accessed on April the 2022)

process. In tabelware and technical ceramics sectors electrical energy is employed for kiln firing in order to achieve required quality. Some manufacturers may also use electricity for transportation [4]. Scheme of main phases with mass and energy flows is reported in Figure 6.

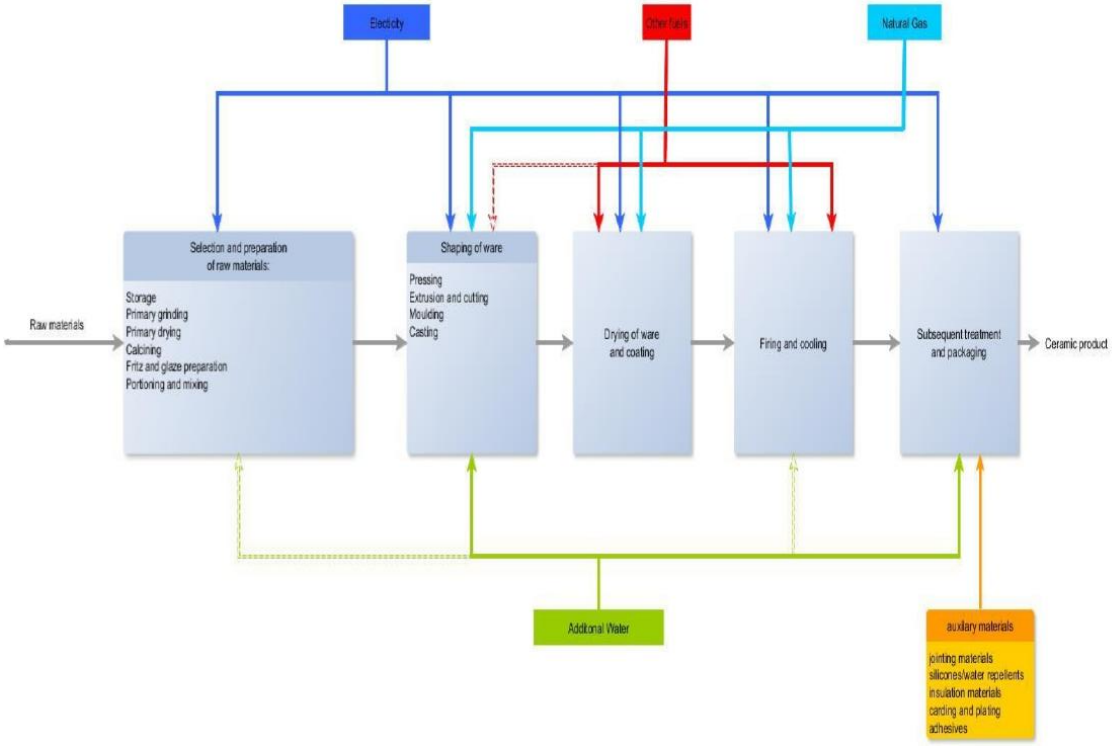


Figure 6 – Overall energy use for the ceramic production process. Source [4].

Ceramics are made from natural extracted materials, but their production is energy intensive and generates emissions. At all levels of production, the European industry is working together to reduce these emissions. For example, the CO_2 emitted to produce the clay blocks for one square metre of an external wall has on average been reduced to approximately 50% between 1990 and 2020, and for one tonne of wall and floor tiles the energy used was reduced by 47%. Total CO_2 emissions in the ceramic industry in the EU fell by more than 45% since reaching a peak in the year 2000[7]. Figure 7 shows the energy mix in the EU ceramics sector. There has been a clear trend to use natural gas in the sector from 1960. In that year, the energy mixture of the sector was covered by the consumption of coal, oil and petcoke. From 2004 there has been some input of biomass in the industry.

[7] https://www.ceramicroadmap2050.eu/ (accessed on April 2022)

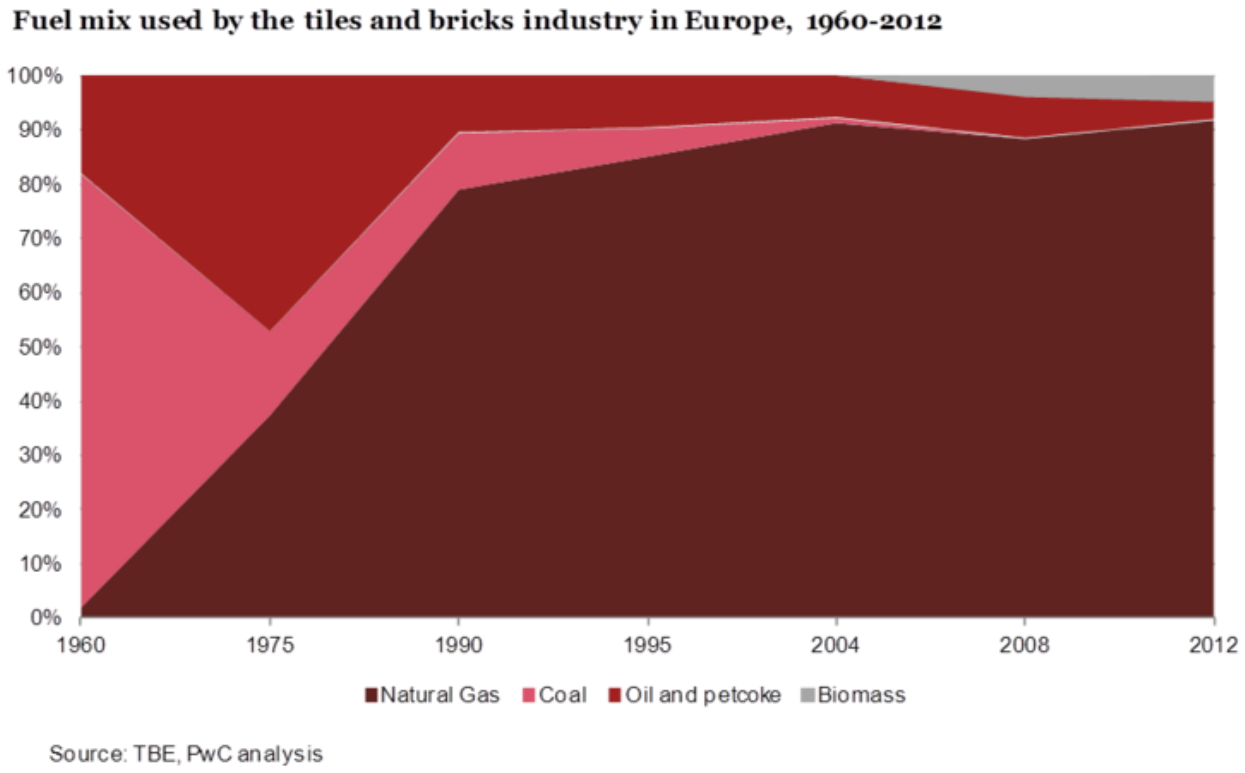


Figure 7 – Fuel mix by the tiles and bricks industry in Europe from 1960 to 2012. Source8.

The available estimation of the energy consumed by the ceramics sector is shown in

Table *3* [3][4].

Table 3 – Estimation of share of energy consumption of sub-sectors for EU15 in the year 2000. Sources: [3][4].

Product	Production (Mt)	Specific energy consumption (GJ/t)	Energy consumption (TJ)	Relative share of energy consumption (%)
Wall and floor tiles	25	5.6 – 5.7	143.5	42
Bricks and roof tiles	55	2.31 – 2.38	130.9	38
Refractory products	4.5	5.41 - 5.57	24.34	7
Table and ornamentalware	0.5	43.46 - 45.18	21.73	6
Sanitary ware	0.5	21.87 - 20.88	10.44	3
Technical ceramics	0.15	34.72 - 50.39	5.2	2
Vitrified clay pipes	0.7	5.23 – 6.10	4.27	1

[8] http://www.tiles-bricks.eu/industry (accessed on April the 2022)

All ceramic sectors are considered energy-intensive because the energy consumed in producing them represents about 30% of the total production cost [5]. The IEA estimates that, worldwide, emissions emerging from the ceramic industry surpass 400 Mt CO2/year from calcination of carbonates and energy end-use. In the EU, the wall and floor tiles, bricks and roof tiles, and refractories sectors emit a total of 19 Mt CO_2. Of these emissions, 66% are due to fuel combustion, while electricity and process emissions represent 18% and 16% of total emissions, respectively [5].

Producing ceramics is an energy intensive process. Total emissions from the EU ceramics sector amount to 19 million tonnes of CO_2 annually [5]. This is roughly 1% of EU' total emissions covered by the EU Emissions Trading System (ETS). Emissions linked to ceramics production can be broken down into three main categories (Figure 8):

- Fuel combustion for drying and heating process.
- Process emissions generated by mineralogical transformation of the clay.
- Indirect emissions, mainly from electricity production.

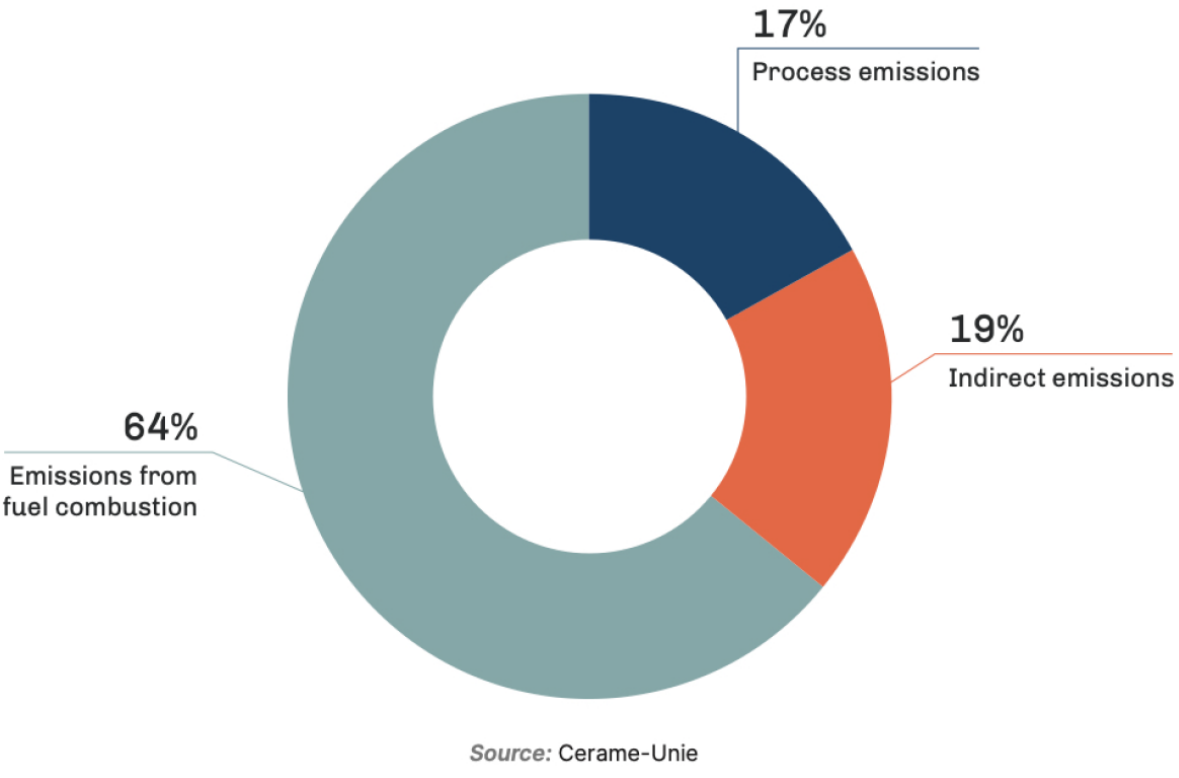


Figure 8 –Share of emission sources in the ceramic industry in 2020. Source: [1].

Around 90% of emissions comes from three sub-sectors: bricks and roof tiles, wall and floor tiles and refractories. The proportion between the different emission types varies significantly, depending on different process, plants, products, and raw material. Particularly for process emissions which

represent 30% of total emission in the bricks and roof tiles sector and can be as high as 60% of total emissions in the clay blocks sub-segment.

Emissions from the ceramics industry depend on two factors, the chemical transformation from raw materials employed during the manufacturing process and fossil fuels used. Direct process CO2 emissions can also emerge from the combustion of the organic matter present in the raw materials or organic admixtures in the manufacturing process. There are also indirect CO_2 emissions, which stem from electricity and raw material preparations. In addition to CO_2 emissions, chlorine, fluorine, sulphur, and nitrogen oxides emissions are released in the manufacturing processes. However, emissions from the ceramic industry have been mitigated in the past years. For instance, fluorine emissions have been reduced by more than 80% in the last decades. Similarly, in industrialized countries, thermal and CO_2 emissions have decreased due to the use of natural gas and by adopting novel technologies (e.g., cogeneration systems, single firing, and roller kilns) [5].

Overall, the ceramics industry is natural gas-intensive, with an energy mix accounting of 85–92% gas and 8–15% electricity. The intensive use of gas is well illustrated in Turkey, where this industry accounted for over 12% of the total natural gas consumption in the manufacturing sector. Gas is fundamentally used to reach high-firing temperatures ranging between 800ºC and 1850ºC. However, refractory and technical ceramics manufacturers employ electric arcs for higher firing temperatures to reach 2750ºC. During the manufacturing process, the main energy end-use is for the drying, firing and cooling stages. The firing stage accounts for about 75% of the total energy cost and more than 50% of all required energy during the manufacturing process. One study indicates that the world's annual energy end-use for firing ceramics through the use of natural gas is estimated at 182 TWh, with the firing process generating around 265 kg CO_2/t of fired tile. Another study suggests that more than 80% of GHG emissions occur in the firing and drying stages [5].

During the manufacturing process of ceramics, plants demand significant amounts of heat for drying and to remove the water from the material. In most cases, manufacturers rely on fossil fuels to evaporate the water. For instance, the energy end-use for dry grinding is approximately 60 kWh, accounting for up to 20% of the total thermal energy end-use during the manufacturing process of dry clay types. Therefore, this process is complex and expensive and demands strict control of process variables to guarantee the quality of the final product. Although drying systems have evolved with the deployment of novel technologies, energy end-use at this stage certainly remains high [5].

CO_2 emissions from ceramic tiles are divided into two categories, combustion and process emissions. The first relates to the emissions resulting from the exothermic combustion reaction between the fuel and the oxidizer. The latter is associated with the emissions emerging from the



decomposition of the carbonates present in the raw materials in the firing stage. During the tiles manufacturing process, thermal energy is required during three phases: drying the freshly formed tile bodies, tile firing, and ceramic slurries. Figure 9 breaks down thermal energy end-use in the manufacturing process [5].

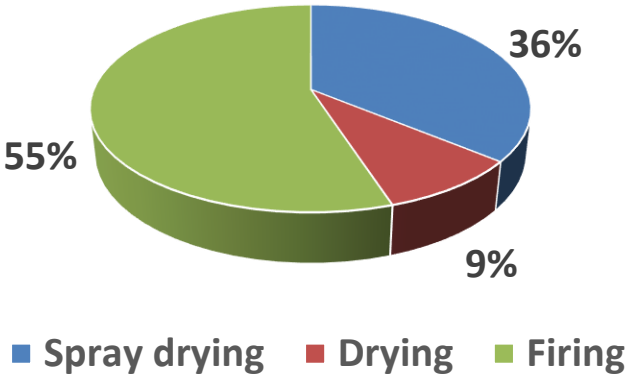


Figure 9 –Breakdown of thermal energy end-use for the ceramic tile manufacturing process. Source: [5].

2.7 Circularity and best practices in the ceramic industry

The transition to a competitive low-carbon and resource-efficient economy in 2050 represents a challenging target for the European ceramic industry. As demonstrated in its long history, the sector is committed to contributing responsibly to the achievement of such a target. This enormous challenge means we need to build on our current know-how and expertise and new breakthrough technologies will be needed.

The 2050 emissions reduction targets are even more challenging for a capital-intensive sector with long investment cycles like ceramics. Kilns for ceramic production can last more than 40 years. Therefore, 2050 is less than the lifetime of a new kiln away. The model developed in the EU Ceramics Industry Roadmap shows that even in the hypothesis where half of all kilns are converted to electricity in the period 2030-2050 and the remainder retrofitted to syngas or biogas co-fired with natural gas, the emissions could only be reduced by around 78% compared to 1990 levels instead of the 83-87% industry target set by the European Commission, mainly due to unavoidable process emissions.

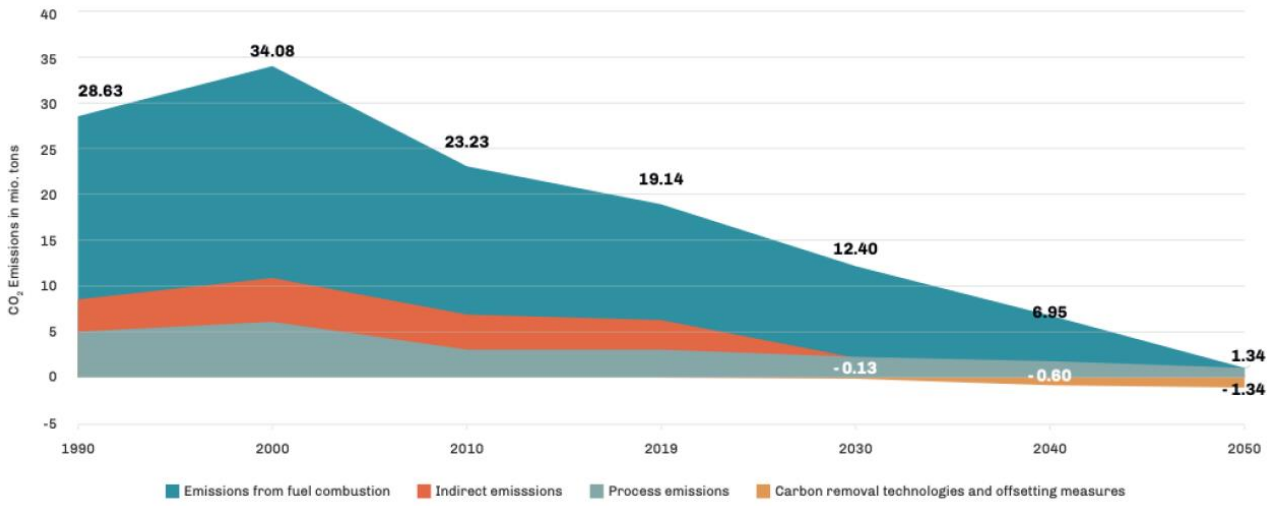
The Ceramics industry's carbon commitment covers not only the production processes of the European ceramic industry but impacts the many other sectors that rely on its products. As the

renovation and upgrading of residential and public buildings gathers pace, the sector is ideally placed to contribute to ensuring the highest standards of energy efficiency and the least possible energy leakage. A broad range of ceramic products, ranging from clay blocks with inherent insulating qualities to ventilated cavity walls and clay facades or roof tiles, all help make buildings more energy-efficient. In energy-intensive industries, refractory products help contain energy where it is needed, minimising energy wastage[9].

The EU ceramic sector has reduced its total emissions by around 33% since 1990. By the decade that begun in 2000, the industry has decreased its emissions by 45%. This has been possible by optimising processes, making production more efficient and by fuel substitution. The most significant reduction in carbon emissions occurred in the 80s when the EU ceramics sector switched from solid fuel (mainly coal) to natural gas (see also Figure 7).

The emissions reduction model by the EU ceramics sector combines a range of measures to achieve a gradual reduction of emissions to reach carbon neutrality by 2050 (Figure 10 –CO2 reduction pathway. Source: [1].):

- Switch to renewable energy sources like green hydrogen, biofuels and decarbonised electricity.
- Reduction in process emissions.
- Innovation and increased efficiency in the manufacturing process.
- CO2 capture CCS/CCU.
- Other carbon removal technologies and offsetting measures.



[9] https://www.ceramicroadmap2050.eu/ (accessed on April 2022)

Figure 10 –CO2 reduction pathway. Source: [1].

Resource efficiency is not only about 'using less', but also 'using better'. Clay is a widely, endless available raw material. Ceramic products are resource efficient and stand out with their high durability thanks to their long lifespan. After the end-of-life stage, ceramic products can be reused, recycled, or recovered. The ceramic industry has developed innovative solutions with the aim of minimising the raw material consumption and waste generation during the production process, through the reuse of waste from other industrial processes, an optimised raw material selection and product design, and supply chain cooperation in the case of recycling [6].

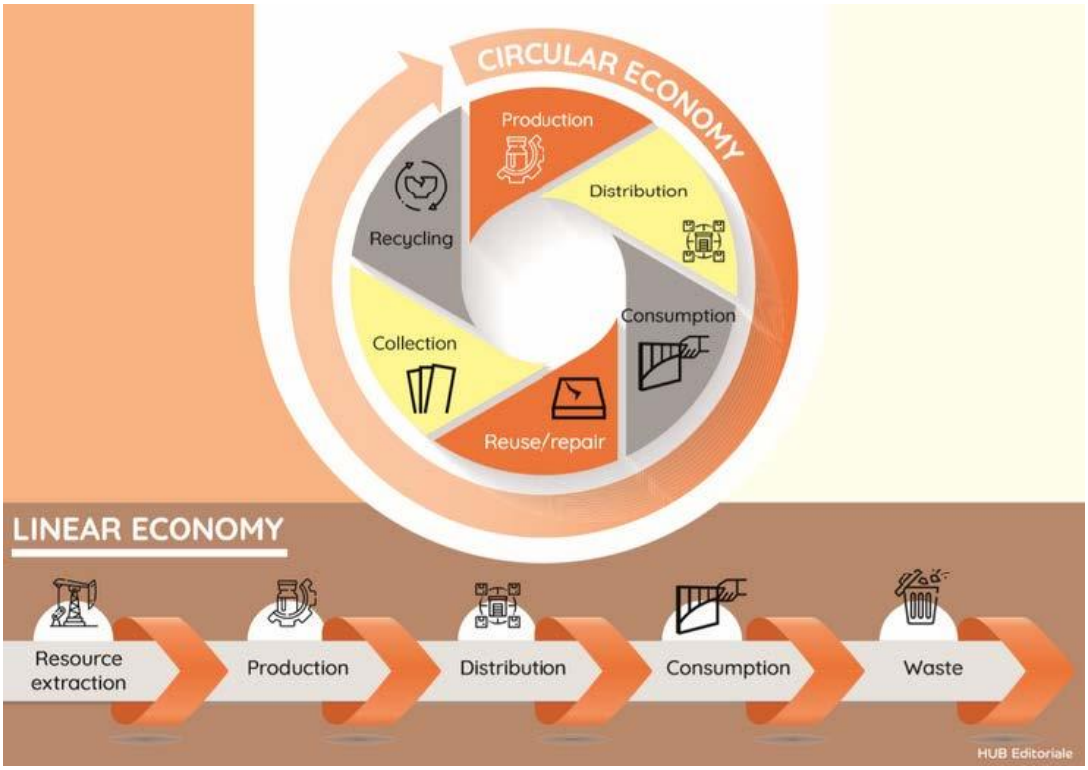


Figure 11 –CO2 reduction pathway. Source: [6].

2.7.1 Bricks and clay blocks

In most European countries, the use of internal production residues from brick production as a substitute for raw materials is common practice. Manufacturers are reintroducing scrap material, such as the dust generated from the grinding of clay blocks, into the raw material mixture for the production of new clay blocks. Some of the poreforming agents used to optimise thermal insulation properties are secondary raw materials from external organic sources, such as saw dust, rice husks or sunflower seed shells.

Waste content from ash products, hydrocarbons, industrial minerals and minerals can be also

recycled into the production process as secondary raw materials. Broken clay blocks can also be crushed to a defined grain size distribution and used as a light weight aggregate in the production of concrete blocks.

Dry stack systems for facing bricks have also been developed. As the walls can be easily dismantled, main benefit provided by this system is that bricks are reusable. Bricks can also be reused when using lime mortar for the brickwork. Brick manufacturers have also developed hanging systems where bricks or brick slips glued on panels are detachably connected to an underlying frame to be easily reused.

2.7.2 Roof tiles

Roof tiles are easy to disassemble and have a very long service life. After the end of life, roofing tiles can be reused as such or recycled in other areas: backfilling in pits and quarries, water-bound cover layer, aggregate for substructure or surface layer in road construction, cover layer of tennis courts and sports fields, vegetation substrate, roofing substrates for green roofs.

2.7.3 Clay pavers

Ceramic pavers are almost always reused and they even increase in economic value. Clay pavers have a reuse percentage of at least 90% and an average lifespan of 125 years.

2.7.4 Wall and floor tiles

A project gathering Spanish manufacturers of ceramic tiles aims at achieving zero-waste in the manufacture of ceramic tiles. A new type of ceramic tile for outdoor application has been developed, incorporating high content of ceramic waste in the body and glaze. Other energy-intensive process wastes (from power plants or glass manufacturing) are also considered. In addition to that, a highly sustainable body preparation process for manufacturing the ceramic tiles has been designed, based on dry milling technologies, capable of recycling all type of ceramic wastes. Achieved results were 20% reduction of waste disposal, 65% saving in water consumption, 30% saving in energy input and 30% reduction in CO_2 emissions.

A project gathering Italian tile manufacturers aims to develop ceramic tiles made from over 70% and up to 85% recycled materials from urban and industrial wastes (e.g. soda lime glass cullet waste, green scrap tiles generated during the industrial process) in substitution of natural raw materials. The combination of these different wastes enables the production of ceramic tiles with similar or improved mechanical properties with respect to the traditional ones.

A Portuguese manufacturer has created a porcelain stoneware flooring for interior areas, designed



following sustainability criteria. This ceramic tile is removable and reusable and does not need any glues, cement or specialised workmanship. As the ceramic tile can be reused, the life span has been extended, leading to less waste production. It also does not need any complementary products of application by implying reduction of material.

2.7.5 Refractories

Refractories are materials designed to withstand very high temperatures. Refractory products are a vital element in all high temperature processes, such as metals making, the production of cement, petrochemical processes, glass and ceramics.

In the refractory industry, manufacturers can produce monolithic refractories and refractory bricks that contain between 20% and 80% of recycled material. Virgin refractory materials can be substituted by recycled material coming from various industries (e.g. iron, steel, metallurgical industries, alumina, ceramic, cement). Materials are then sorted, crushed, dried and possibly milled. These products are tailored to the installation method as well as the application conditions of customers.

As an example, one manufacturer produces refractory bricks for the cement industry that contain up to 55% of recycled material. Based on this composition, a high resistance against alkali attack is achieved, which is often a major issue in the cement manufacturing process. Recycled materials play an important role in the research and development of these products as they have a significant impact on the behaviour and performance of the corresponding monolithic and brick refractories.

2.7.6 Sanitaryware

In the sanitaryware industry, porcelain shards can be used as by-product materials by the feldspar extractive industry. Porcelain shards are crushed and grinded before being dispatched. Plaster moulds can also be used as by-products by the gypsum extractive industry for quarry restoration or in the production of aggregates. These processes reduce the use of primary raw materials, decrease pollutants released into the environment due to the extraction of raw materials and save costs.

A manufacturer from Portugal has created a new material with high incorporation of waste that competes with common stoneware. This unique material is formulated to reintegrate all the resulting waste from its own processing, as well as part of the waste produced during the processing of chinaware. Moreover, no additional treatment is required before integration in the sanitary ceramic manufacturing process circuit, since it uses the same means from the preparation of raw material to the final firing, keeping up with the ongoing chinaware workpieces in the production chain.



2.7.7 Tableware

Porcelain tableware of high quality is a durable product that can be used effortlessly for decades. As ceramic is inert at temperatures below 200° C, ceramic tableware products can be washed for a very high number of times without any visible changes. Due to their specific properties (e.g. handpainted porcelain, porcelain with precious metals), artistically high quality tableware products should be washed more gently by hand.

In the tableware industry, most manufacturers are developing solutions to reintroduce processed water and material residue in the production process. A French manufacturer is producing recycled household goods made from a natural paste formed by treating mineral materials and manufacturing sludge, recycling up to 25% of their industrial residue. A manufacturer from Germany recovers up to 98% of solid material residue (unfired and fired porcelain mass), reintroduced as secondary raw material in the porcelain production process. Water used in the manufacturing process is also treated and reincorporated in the production process by using a combination of process optimisation measures and sewage treatment systems. A manufacturer from Italy is following this practice as processed water and material waste are reused to produce their tableware. Material waste that cannot be recycled is delivered to an external recycling plant. A Spanish manufacturer is also recycling ceramic food packaging products to powder that can be used for road and pathway construction among other. The ceramic food packaging can also be used for other purposes (e.g. table- and kitchenware, pencil cubes or flower pots).

2.7.8 Expanded clay

Expanded clay is a lightweight aggregate that is produced from natural clay. It is suitable for a wide range of applications in the construction sector, such as housing and infrastructure. It can be used in green applications such as in hydro-culture and technological applications (water treatments, roofgardens).

In the expanded clay industry, up to 90% of the product can be reused. It is also resource efficient as 1m³ of natural clay will result in about 4m³ of expanded clay. Up to 100% of expansion clay additives and 10-15% of virgin clay can be replaced by alternative materials derived from other industry sectors. Manufacturers of expanded clay use waste as additives or fuels, hence reducing the need for virgin raw material. As an example, a Belgian manufacturer uses iron oxides coming from the steel industry as additives. This iron oxide is needed in the bloating process as the boom clay does not have chemical properties that could make the expansion possible as well as providing support to reduce the energy in the overall process. Such additives come from oil refineries, vegetable oil producers, bio-diesel, steel production or treatment, industrial and municipal waste



water cleaning, mineral wool and other types of wastes.

2.7.9 Clay pipes

In the vitrified clay pipes industry, a manufacturer is producing clay pipes which are 100% recyclable, consist of about 40% secondary raw materials on average and have a service life of more than 100 years. The minimum share of external recycled content in the raw materials used has been increased, on average, over 20%. Scrapped content from other clay productions such as tiles and sanitaryware can be used as secondary raw materials. The internal recycled content from scrap and auxiliary materials leads to a total recycled content of over 60% at maximum. The non-conform products (scrap) that didn´t pass the quality check at the dryer or the kiln are crushed and used as raw material again. This also applies for auxiliary ceramic materials that used to support the pipes in the kiln and for cut-off material. The use of secondary raw materials leads to less scrap during the production due to an increased resilience and also reduces energy consumption in production. The circularity of the process from mining clay to recycling of vitrified clay has also been optimised with the cradle-to-cradle® certification process.

2.8 Energy efficiency and decarbonisation innovations

Table 4 presents the main technologies deployable in the ceramic industry to contribute to climate-neutrality targets. The table also shows the advancement of the technology. Not all technologies might be applied to all sub-sectors. For these technologies to develop and to be applied, several conditions are essential. In particular, the support of industry regulators.

Table 4 - Decarbonisation technologies for the ceramics sector.

Subsector	TAS				
Microwave-assisted drying		2			
Heat pumps				4	
Biomass					5
Biogas				5	
Syngas		2			
Green hydrogen		2			
Electrification		2			

CCS - CCU	1				

Source: [1]. Technological advancement status (TAS): 1-low advancement, 5-fully available.

The CO_2 reduction model by the EU ceramics sector assumes that:

- There is a constant level of production and a similar product mix between 2020 and 2050.
- The real emissions for the year 2019 were taken as basis for the estimations, as 2019 was a more representative year in terms of production levels (due to the COVID-19 pandemic, the year 2020 was not a representative year, as the emissions were exceptionally low during this period).
- Zero-emissions technologies, especially for the firing process, will be available in a relatively short term, so as to allow the progressive renewal of assets, whose operational lifetime often exceeds 20 to 30 years.
- All barriers regarding the availability of alternative fuels (such as green hydrogen or biogas) are overcome, and that these fuels are made available in sufficient amounts and with a competitive price through Europe.
- Obstacles for the technical application and availability of alternative fuels will progressively be removed from 2030 and would allow the industry to move to breakthrough solutions, such as hydrogen, biogas or electricity in equal proportions.
- A gradual decarbonisation of the power supply through Europe.
- Gradual availability and acceptance of CCUS.

2.8.1 Switching to renewable energy

More than four fifths for the industry emissions come directly from its energy use. A switch to renewable energy, whether renewable electricity, green hydrogen, green synthetic gas or biofuels, will reduce emissions. The industry's roadmap is based on a gradual decarbonisation of the power supply and an increased availability of green hydrogen, green synthetic gas and biofuels.

Depending on the type of plant and local availability options, some plants could switch to decarbonised electricity whilst others could eventually use biofuels, green hydrogen, or green synthetic gas. Since kilns can be used for more than 40 years and a switch of fuel type represents a major capital investment (except for a switch to biogas for plants that currently use natural gas), the choice of energy type and the availability of a regular and affordable fuel supply are necessary and vital.

The ceramic industry is committed to continued improvements in the energy efficiency of

installations, to reduce the overall energy demand. This includes the increased use of recycled material, the adoption of best available technologies and best available management practices, and the embrace of new technologies.

Available technologies and management practices include the installation of improved kilns, dryers, thermostats and seals as well as implementing automated controls. Heat savings can also be achieved by improving thermal insulation through the use of novel refractory linings, coatings and other ceramic materials.

Recovery of excess heat is also an important way to reduce fuel consumption. This can be done by capturing kiln gases to preheat the combustion or dryer. Smart design of manufacturing facilities is also a key factor because the physical distance between the different processes, such as firing and drying, can lead to energy savings.

Under the vision of a climate-neutral industry, in 2050 the European ceramic industry has projected an energy need of around 140k TJ. This would be one third less than in 2020 (Figure 12).

Biogas and green synthetic gas technologies are already available, with varying levels of penetration in different member states, and the technology can be scaled up. The industry has therefore included these renewable gases in its energy mix for 2030. Available volumes are expected to rise until 2040 and 2050, but compared to hydrogen and electrification, biogas and green synthetic gas will play a smaller role.

Until 2030, the industry expects small quantities of green hydrogen to be available for the ceramic sector due to the demand of other sectors, pricing issues and the lack of infrastructure in EU. The ceramics sector expects an increase in the availability of green hydrogen from 2040.

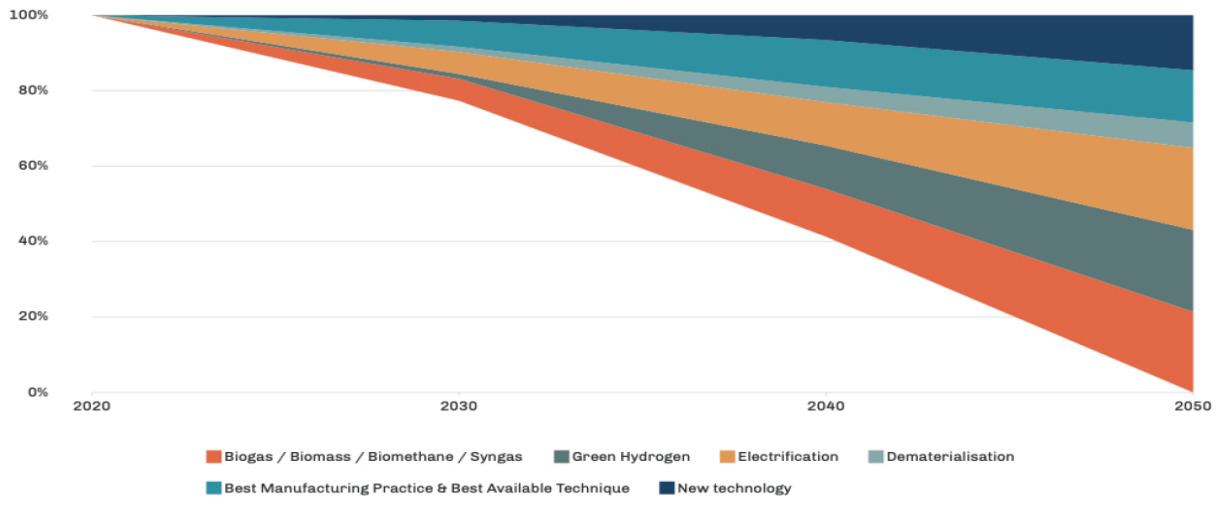


Figure 12 – Measures contributing to the reduction of emissions form fossil fuel consumption. Source: [1].

2.8.2 Annual alternative energy needs

Figure 13 presents the annual alternative energy needs of the ceramics industry to achieve the carbon neutrality target by 2050. The ceramics industry will nearly need 50k TJ each of green hydrogen, biogas, and green electricity by 2050. These amounts are not currently available to the industry. Their supply does not exclusively depend on the industry but on many factors, such as infrastructure and the right legal and policy framework.

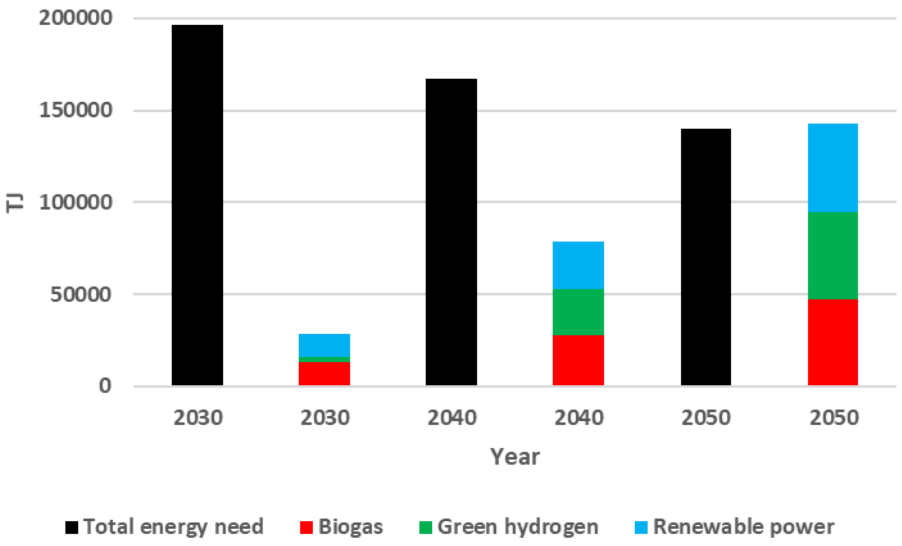


Figure 13 – Alternative energy needs derived from emissions reduction. Source: [1].

2.8.3 Cost of decarbonising the European ceramics industry

According to the European Ceramics Industry Association (Cerame Unie) the costs to reach carbon neutrality will grow sharply in time (Figure 14). By 2030, the annual decarbonisation cost will exceed €500 million. The annual costs will progressively grow to nearly 1 bn EUR per year in 2040 and will exceed 1.2 bn per year in 2050. The total accumulated costs until 2050 are estimated at around 27 bn EUR.

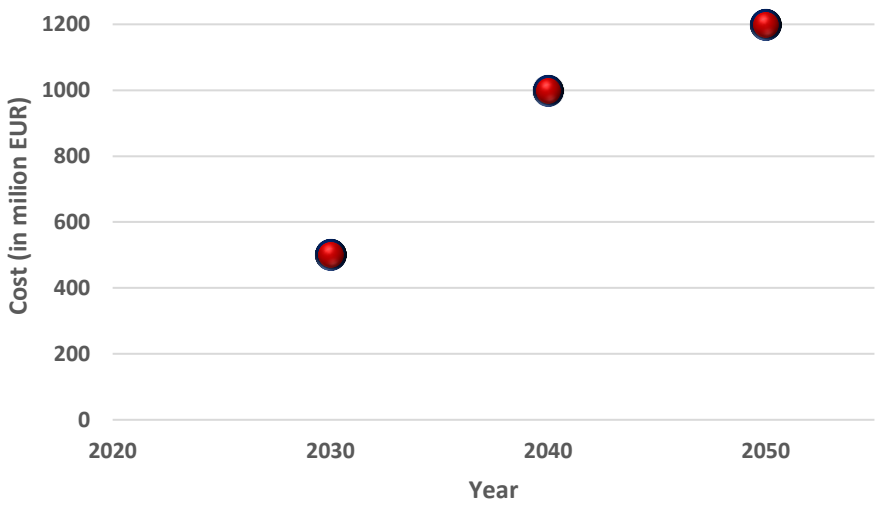


Figure 14 – Cost of decarbonising the European ceramics industry. Source: [1].

2.9 Options for decarbonisation

For the last decades, energy efficiency improvements have been made in the European ceramic sector, resulting in more efficient kiln designs and drying techniques. In addition, the drying and firing process has become a continuous process (creating a stable energy demand). However, further decarbonisation is required to achieve net zero (fuel) CO_2 emissions. The Royal Dutch Building Ceramics Association has developed a 'Technology Roadmap' [2]. This roadmap will, among others, elaborate on the energy transition and carry out research for the ceramic industry within the Netherlands.

Different options for decarbonisation are described in the cited Roadmap, categorised according to the overview in Figure 15. The relevant categories are fuel substitutions, process design, use of residual energy and CO2 capture and storage (or utilisation).

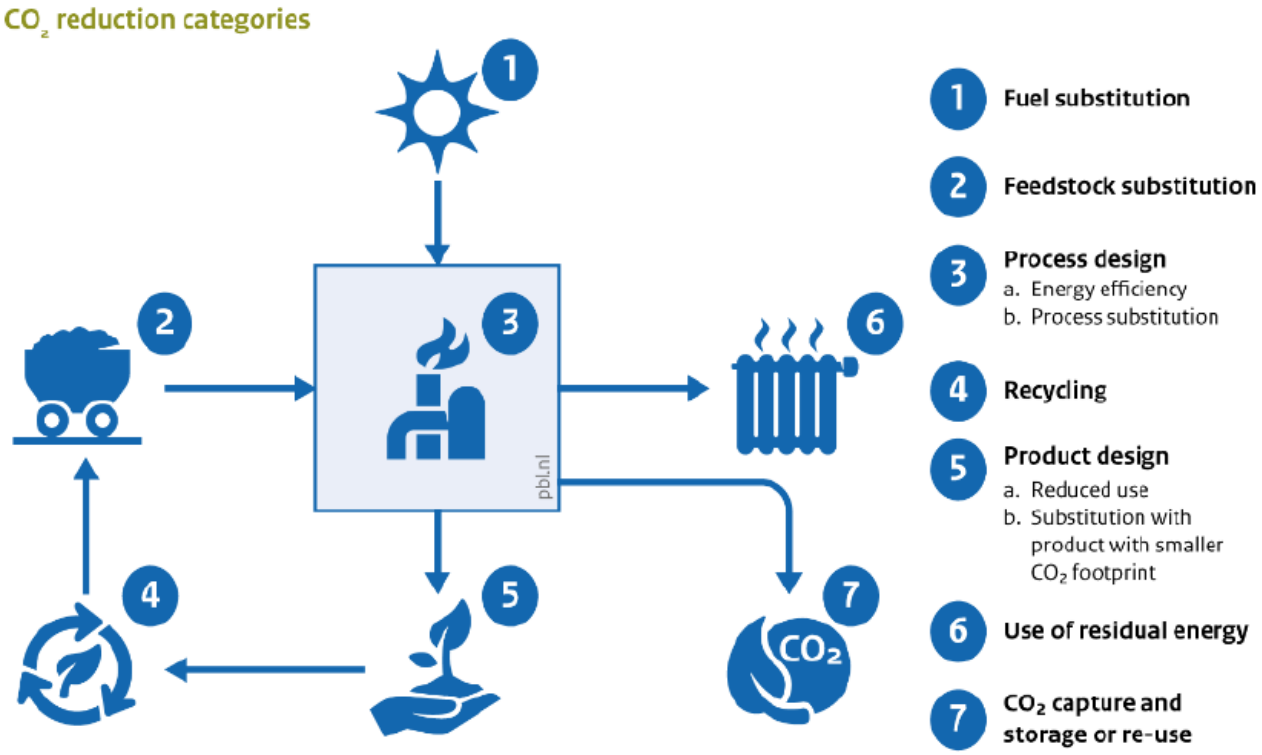


Figure 15 – Different CO2 abatement categories identified by the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN). Source: [2].

Table 5 provides an overview of the different decarbonisation options that are applicable to the ceramic industry in the Netherlands, but these could also be applicable in the rest of the EU countries due to the process similarities in the industry.

Table 5 - Overview of abatement options, including the category, relevant process, maximum CO2 abatement and availability. Source [2].

Name option	Category	Process(es)	Maximum CO_2 abatement	Availability
Green gas	Fuel substitution	Drying/Firing	74%	Commercially available
Hydrogen	Fuel substitution	Drying/Firing	74%	Lab scale
Electric heating	Fuel substitution	Drying/Firing	74%	Concept
Microwave radiation	Fuel substitution	Drying/Firing	74%	Concept
Heat exchange	Use of residual energy	Drying	26%	Pilot scale
Heat pump	Use of residual energy	Drying	26%	Commercially available (for the relevant temperature)
Hybrid drying	Use of residual energy	Drying	Varies	Pilot scale
Ultra-deep geothermal	Process design	Drying	26%	Commercially available, but not yet in The Netherlands
Extended tunnel kiln	Process design	Firing	26%	Commercially available
CCS or utilisation	CCS or re-use	Firing	90%	Commercially available[9]
Lighter bricks	Product design	Firing	Unknown	Concept

2.9.1 Green gas from gas grid

Alternative carbon neutral fuels such as green gas and hydrogen, and renewable electricity can substitute the natural gas that is used for firing and drying by the ceramic plants. The impact of hydrogen on the product still needs to be tested.

Green gas (also named ‘biomethane’) can directly replace natural gas. Green gas can be produced using anaerobic digestion or gasification technology. Anaerobic digestion is preferred for wetter biomass material and gasification is preferred for dryer biomass material.

If green gas is produced on a large scale centrally and inserted into the gas grid, no changes would be required for the ceramic industry to decarbonise the ceramic production process fuel-related CO_2 emissions, as the natural gas consumption from the grid would be replaced by green gas consumption from the grid.

2.9.2 On-site biogas from anaerobic digestion of biomass

If green gas from the grid is not available, on-site anaerobic digestion could be applied. Anaerobic digestion is a biological process where bacteria break down biomass material in the absence of air. The biogas that is formed is composed approximately of 60% methane and 40% CO_2 [7]. The feedstock material for anaerobic digestion is often waste – such as food waste, agricultural waste, waste from water treatment and municipal waste – but can be any type of non-woody biomass. The biogas can then be converted into green gas by removal of non-methane elements (mostly carbon dioxide) [8]. During the digestion process, the required heat is obtained by burning part of the produced biogas.

Table 6 – Parameters for a large-scale production unit of green gas using anaerobic digestion of biomass. Source [2].

Parameter	Unit	Value
Green gas production per year	GJ	150,000
Investment costs	M€$_{2019}$	6.9
Fixed O&M costs per year	M€$_{2019}$	0.6
Feedstock (waste) costs	€$_{2019}$/GJ	8.18[1]

2.9.3 On-site syngas from biomass gasification

If green gas from the grid is not available, on-site gasification could also be applied. Gasification of biomass (organic material) is a thermochemical process that produces syngas. The syngas is composed of methane, hydrogen, CO and CO_2 and is used as fuel or feedstock and can also be upgraded into green gas. Producing syngas at the site of a ceramic plant would require a 'bio-SNG-centrale' that produces green gas in three steps: First, gasification takes place, then the gas is cleaned from unwanted elements, and finally it is upgraded conform to the quality standards of natural gas. Table 7 shows the associated parameters and costs for production of green gas by gasification of biomass for a reference installation.

Table 7 – Parameters for a large-scale production unit of green gas using gasification of biomass. Source [2].



Parameter	Unit	Value
Green gas production per year	GJ	567,000[1]
Investment costs	M€$_{2019}$	56.7
Fixed O&M costs per year	M€$_{2019}$	3.99
Feedstock (biomass) costs	€$_{2019}$/GJ	5.00[2]

2.9.4 Hydrogen

Hydrogen is a fuel substitution but, unlike green gas, it does require a few adjustments to the manufacturing process. The applicability of hydrogen depends on the firing kiln design and will also require investments in modified burners. Firing by hydrogen results in higher temperatures, which leads to an increase in NOx emissions. This, and the potential negative impacts of the fuel switch on the product quality requires further research before hydrogen can be considered fully applicable as fuel substitution.

Hydrogen fuel can be categorised based on their production process: grey hydrogen, blue hydrogen, green hydrogen, by-product of other production processes. Grey hydrogen is produced via steam methane reforming (SMR) with natural gas as fuel and is therefore not fossil free. Blue hydrogen is also produced via SMR but combined with capturing and storing of related carbon emissions. Green hydrogen is producing hydrogen via electrolysis. Green hydrogen production is currently three times more expensive as producing grey hydrogen.

The existing gas infrastructure (i.e. pipelines and storage tanks) can potentially be used when the natural gas is fully substituted by hydrogen, with only a few adjustments required due to the lower density of hydrogen. It is unknown if and when large amounts of green hydrogen will be produced and inserted into the gas grid.

According to the Technical Center for the Ceramic Industry Foundation (TCKI) in The Netherlands[10], the application of hydrogen in the ceramic industry requires the following:

- Transporting hydrogen instead of natural gas through pipelines has a capacity loss of only 10% in terms of energy.
- 58% more water content in flue gases (might be an opportunity in recovering latent heat).
- Less environmental air is needed for mixing before hydrogen enters the burning installation.
- No problems will occur with reaching the desired flame temperature.

[10] https://tcki.nl/en/

- When firing frequency is high enough, flame strikes are prevented.

It is currently unclear what burner modifications are needed (further research is proposed), how use of hydrogen in firing will impact the quality of the ceramic products, and what the corresponding techno-economic characteristics, like CAPEX and OPEX, of these hydrogen burners would be for the ceramic industry.

2.9.5 Electric heating

Electric heating could potentially fully replace the use of natural gas and related CO_2 emissions in the fire kiln by using renewable electricity as energy input. Furthermore, the extra heat that is required for drying could also be supplied by electric heating. On a smaller scale, this technique is used by pottery bakers. However, the production capacity of these installations cannot be compared to large scale ceramic plants. Electric furnace kilns have not yet been implemented on a large and continuous scale (i.e. in tunnel kilns). The feasibility of applying electric kilns in large scale ceramic production plants therefore remains unproven. In addition, electrification of the furnace will significantly increase the onsite electricity consumption. It is uncertain whether the capacity of the local electricity infrastructure would be able to supply this electricity as ceramic production plants are located typically in more rural areas.

The TCKI has performed a simulation in which it compared electric drying with hydrogen and natural gas drying. One of the conclusions of this simulations is that electric drying would be the most energy efficient in terms of amount of air needed, thus resulting in less losses through flue gases. The characteristics of an electric kiln was also simulated for different air inlet temperatures and temperature of heat flows within the kiln and compared to a reference natural gas fired kiln. The simulation results show that theoretically an electric kiln would be possible, with an electrical power requirement of up to 10 MW, but this will be a huge challenge. In addition, the impact of using electric heating for firing on the ceramic products of large ceramic plants requires further research.

2.9.6 Microwave radiation

Microwave assist technology (MAT), electromagnetic radiation, is a potential technology for heating ceramics to improve energy efficiency and lower CO_2 emissions. This option is applicable to the drying or firing process by transferring microwave energy to the ceramics. The microwaves have different frequencies, of which the working frequencies for microwave materials processing furnaces are 915 MHz to 18 GHz. The difference compared to conventional heating (transferring heat through conduction, convention and radiation) is that electromagnetic heating converts the electromagnetic energy into heat within the centre of the material, on atom level. In other words, heating is performed



from the inside of the material instead conventional heating from the outside. The effective heating through microwave radiation depends on the ability of the material to transfer microwave energy into heat, defined by the dielectric loss factor. Resulting from this, three categories of material can be defined:

- Transparent: microwaves pass without getting absorbed.
- Conductor: microwaves are reflected and surficial heating is created by plasma formation.
- Absorber: microwaves are absorbed and the radiation is converted into heat. Such materials are also called: microwave coupled materials.

A drawback of microwave heating is that the heated ceramics need a higher temperature than room temperature when exposed to a microwave field. Therefore, it is considered to be a complementary technology that should still be combined with conventional or electric heating. The need for an elevated temperature has two reasons: firstly, the chemical reactions (e.g. calcination, sintering) of the heated ceramics demands a pre-heated surrounding and secondly, it ensures uniform heating of the ceramics. This technique is especially suitable for fine grained ceramics and realises a significant decrease in energy use. The energy requirements while using MAT is less than 50% of using conventional heating. The main reason for this difference is the duration of the firing process, which is less than two hours for using MAT and nearly five hours for conventional heating.

This microwave (or infrared) technique could also be combined within an electric kiln to deliver heat more efficiently to specific high temperature sections of the kiln.

A barrier to MAT could be possible risks associated with the microwaves. This might force the plant to change the kiln and dryer design (e.g. adding protecting barriers) and protect its employees from harmful radiation. This new plant design can cause technical and logistic challenges. The effects of microwaves on the properties (such as discolouration) of the final ceramic products are not fully researched yet. The TCKI started in 2019 a research to clarify this matter by applying x-ray differentiation on the ceramic products to measure the sensitivity of specific mineral types to microwaves.

2.9.7 Use of residual energy via heat exchange (heat matrix)

This section discusses the decarbonisation options using residual energy for the drying process of ceramics production. An alternative option, which is not related to the heat supply of the ceramics production itself, is the use of residual energy by external parties, such as other companies or in the built environment.

It is important to note that application of drying decarbonisation options is limited by the degree of waste heat that is already used for drying from the firing section. This is because most plants supply



a significant part (and sometimes all) of the heat required for drying from the residual heat (of the cooling section) of firing process.

A significant amount of heat from the firing kiln is lost through hot flue gases (100 – 200 °C), which cannot be ventilated to the drying process due to the corrosive elements present in these flue gases. By using a heat exchanger, the heat could be transferred to clean drying air and used for the drying process. However, a common problem of such heat exchangers is condensation of water that causes deterioration of the steel pipes of the heat exchanger, leading to holes and subsequently mixing of clean environmental air (which will be ventilated to the drying section) with corrosive flue gases.

The Heat Matrix is an innovative heat exchange method that solves this deterioration problem by using plastic pipes (PTFE) and recirculating part of the heated air through the flue gas section. A pilot version of this technology has been tested and validated. The outcome of this research was positive and showed that 20 – 25 kW of heat could be captured from the flue gasses (0.7 – 0.9 t/hr). The test setup was 20 to 25 times smaller than a real situation, thus theoretically the heat capture could be 400 – 625 kW. Though this is relatively a small capture (0.144 – 0.225 GJ/t), an advantage of this option is that no other alterations to the manufacturing processes have to be made. The TCKI indicates that this technology is an ‘end-of-the-pipe’ option, i.e. useful when all other existing energy efficiency improvements have been implemented.

2.9.8 Heat pumps

Industrial closed heat pumps are applicable to the drying process of the ceramic industry. The heat pump allows waste heat to be upgraded to a temperature that is sufficient for drying.

Table 8 gives the techno-economic parameters which are adjusted to a heat pump applicable to a ceramic plant with a production capacity of 80 kt/y. The heat pump has an expected lifetime of 12 to 15 years and its variable O&M costs are fully dependent on the electricity price, which is set at 0.053 €/kWhe for this example. The efficiency of the heat pump (expressed as the energy output per electricity consumption, or COP) is assumed to be 3.5.



Table 8 – Parameters for an industrial closed system heat pump. Source [2].

Parameter	Unit	Value
Heat (output) per year	GJ_{th}	57,600
Investment costs[1]	$M€_{2019}$	2.28
Fixed O&M costs per year	$k€_{2019}/yr$	52
Variable (electricity) O&M costs	$€_{2019}/GJ_{th}$	4.17

2.9.9 Hybrid drying

The TCKI has conducted research to improve the drying process. The improved technology has been named hybrid dryer and has a lower specific energy use and specific CO_2 emission than regular state of the art drying technology. The difference with regular drying (in drying chambers or tunnel dryers) is the use of two drying phases (in two drying chambers) instead of only one. First aerothermal drying is applied, using significant amounts of air, followed by semi-steam drying which is drying with little air, high temperature and humidity. Aerothermal drying might not be possible during the colder and wetter months of the year, in that case conventional drying should be combined with semi-steam drying. The specific heating requirement lowers from 4-10 GJ/t to approximately 3 GJ/t water that should be evaporated, thus an energy efficiency improvement of 25% to more than 300%. The exact energy improvement for a plant depends on the water content of shaped green ware (ranging from 20 – 30 %) that should be evaporated. The hybrid drying technique makes no or little use of the residual heat from the tunnel kiln, therefore a condition is that no air is forced through the firing kiln during the cooling down of the wares to ensure a real energy improvement. A way to achieve this might be by combining this technology with an extended tunnel kiln.

Specific techno-economic information about applying hybrid drying is not available, but costs will come from adjusting the conventional drying chambers (air intake and exhaust, reinforcement and corrosion protection).

2.9.10 Process design through ultra-deep geothermal

This option refers to the extraction of geothermal energy and its application to the drying process. Geothermal heat is available from different earth layers below the surface. Figure 16 shows such



layers and the corresponding type of geothermal heat that can be extracted from each layer and deepness. Shallow geothermal and deep geothermal do not supply the required heat (i.e. high enough temperature difference). Therefore, only ultra-deep geothermal heat is considered to be applicable to the ceramic industry. The expected temperature that can be achieved by pumping water through such ultra-deep layers is 120 to 140 ºC. The heat can be used in the drying phase of the manufacturing process.

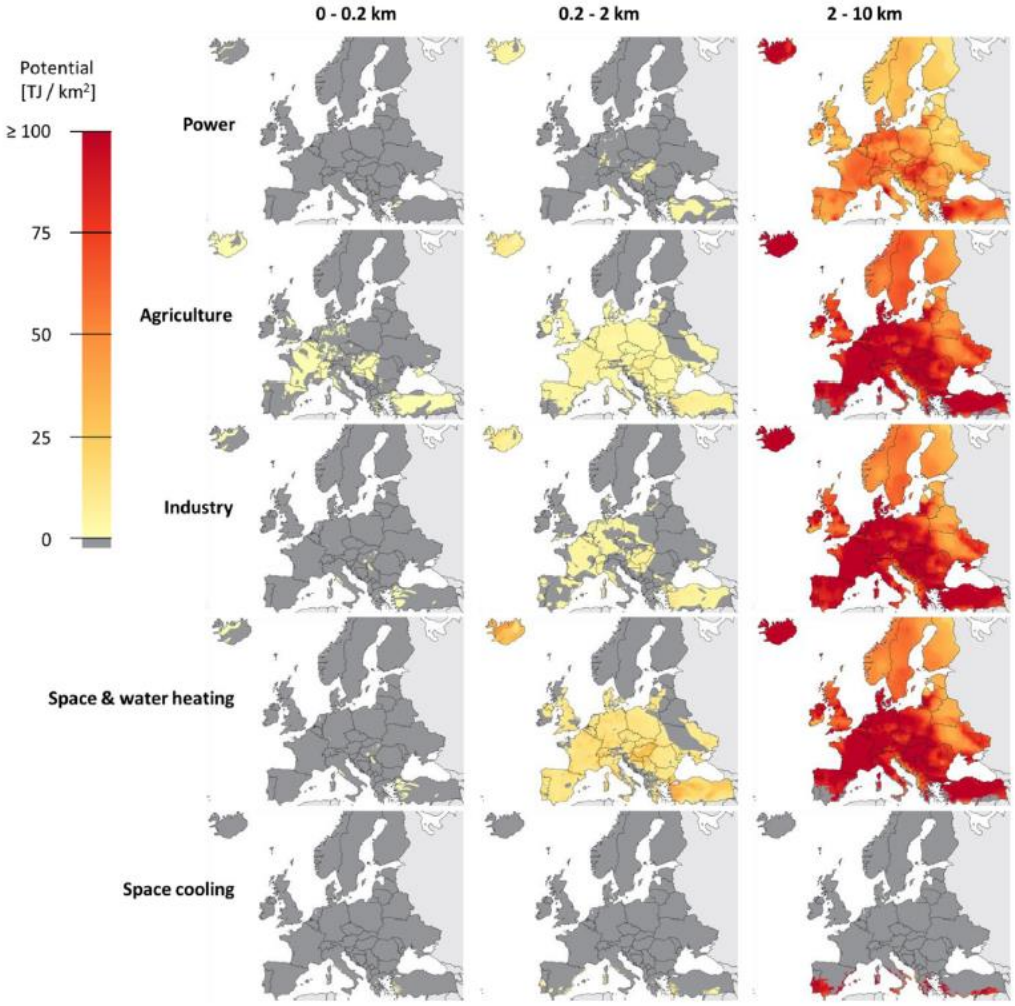


Figure 16 – Long-term economic potentials for various geothermal applications in Europe at three different ranges. Taken from the original source [9] (license: CC by 4.0).

Techno-economic parameters for an ultra-deep geothermal heat installation are shown in Table 9.

Table 9 – Parameters for ultra-deep geothermal. Source [2].

Parameter	Unit	Value
Heat (output) per year	GJ	428,400
Investment costs[1]	M€$_{2019}$	42.7
Fixed O&M costs per year[2]	€$_{2019}$/yr	181,900
Variable (electricity) O&M costs	€$_{2019}$/GJ	2.11

2.9.11 Extended tunnel kiln

The second option is an alteration of the conventional gas-fired kiln, which could also be applied to electric kilns. In 2010, the ceramic sector in the Netherlands initiated the concept of an extended tunnel kiln. This extension is many tens of meters, thus 30 – 50% of the initial tunnel kiln length. This extension allows the bricks to dry without using forced cool air making the tunnel kiln more energy efficient. Another advantage of this concept is that the drying process can be decoupled from the firing kiln, as there is no residual heat from the firing kiln's cooling down section, which is a required condition to apply hybrid drying. A simulation by TCKI shows that gas use lowers from 51 m^3/t to 35 m^3/t (a reduction of 30%) when extending a tunnel kiln with an annual production capacity of approximately 80,000 tonnes.

2.9.12 Carbon capture, storage and utilisation

Carbon capture and storage (CCS) or utilisation (CCU), can in theory be applied to the ceramic industry. It is assumed that post-combustion capture technology would be applied, where the CO2 is captured from the flue gases. By capturing CO2 emissions post-combustion, process emissions are also included in the capture. The capture rate is theoretically possible to be 100%. However, a cost-effective maximum capture rate is set at 90%. The captured CO2 then has to be transported for storage or utilisation. If transport is not possible through pipelines, then it is transported by truck or ship (which would require liquefaction of the captured CO2).

To give an indication of the cost of CCS, a techno-economic analysis by the International Energy Agency (IEA) of post-combustion CO2 capture at gas-fired power plants is used, as the CO2 concentration of the flue gases of both gas fired power plants and ceramic production plants is very low (<5%). The study provides investment and operational cost values (see

Table 10). The investment costs consist mostly of the CO2 capture unit and compressor. The corresponding investment costs per tonne CO2 are based on a given 25 years lifetime. The energy costs are based on the extra energy consumption that is required for regeneration of the solvent and compression of the carbon dioxide. The operational and variable cost refer to routine maintenance costs and other fixed variable costs.

Table 10 – Parameters for carbon capture at a gas-fired power plant. Source [2].

Parameter	Unit	Value
CO_2 capture capacity	Mt/yr	2.5
Investment costs	M€$_{2011}$	602
Fixed OPEX	€$_{2011}$/tCO_2/y	10
Variable OPEX	€$_{2011}$/tCO_2	4
Specific heat consumption	GJ_{th}/tCO_2 captured	3.35
Specific power consumption	GJ_e/tCO_2 captured	0.58

The values in

Table 10 represent a capture unit that is far larger than required for a ceramic plant. When considering the relatively small size of the emission volumes per plant, the specific investment costs (EUR/t CO_2 captured/year) are likely to be significantly higher for a carbon capture installation unit at a ceramic plant. Transport and storage costs of CO_2 is an added challenge since many ceramic plants are situated at remote places, without any neighbouring industries that for example could cooperate storing, using or transporting CO_2. Furthermore, CO_2 is (in 2020) only allowed to be stored in in empty natural gas reservoirs in the North Sea and no gas infrastructure for transporting CO_2 is present yet, which means additional costs for shipping or trucks will be added on top of the fee that is

to be paid to the facilitator of the storage reservoir13. Besides storage, utilisation of captured CO_2 might also be a possibility by supplying CO_2 to greenhouses or to the food and beverage sector.



2.10 Emerging technologies for making ceramic manufacturing more sustainable

Table 11 – Emerging technologies for making ceramic manufacturing more sustainable according to the Level of sociotechnical system. Source [5].

	Technology	Benefits	Energy and/or emissions reductions
Ceramics manufacturing	Vacuum drying	This technique implements reduced atmospheric pressure to decrease the energy end-use needed for the drying process	N.A.
	Microwave-assisted drying and firing	By using microwave heating, energy is delivered more efficiently to dry and fire products. Therefore, reducing energy end-use for the drying process.	This technique delivers significant reductions in energy end-use, which can be as high as 99%.
	Hybrid Kiln	Instead of employing a desulpherised kiln and dryer, exhaust gases are supplemented through a gas-driven heat pump to enhance thermal energy. This approach enables manufacturers to select either electric heating employing CHP as an option and/or primary fuel.	This technology can deliver up to 65% in energy savings.
	Reduction of water content in the shaped product	Most of the energy consumed in the dryers is used to evaporate the water contained in the ceramic products. Therefore, reducing water content will require less water to vaporise and less energy to dry formed products during the drying stage.	N.A.
	Heat pipe heat exchanger	Heat pipe heat exchanger applied to a ceramic kiln employing exhaust gases to preheat water delivered energy recovery rates of about 15%.	Energy savings could reach up to 65%.
	Preheat water added for forming heavy clays	Applying hot water instead of cold during the forming stage reduces the drying heating requirements	This technique can lead to emission reductions of about 3%.
	Controlled dehumidification	The water that is condensed within the chamber releases heat that is supplied in the drying process. This system is entirely closed, and therefore, highly energy-efficient.	The energy savings this technique delivers can be as high as 80%

	Controlled drying air recirculation	In this approach, the inlet and outlet air temperatures remain steady, while the drying agent recirculation coefficient augments. This results not only in reducing the share of new air, but also optimises the air flow.	This technology can lead to energy savings of 25%
	Heat recovery facilities in dryers	Heat recovery enables the drying air to be replaced with hotter gases from other manufacturing processes. Such gases can come from cogeneration engines or the kiln.	This technology can mitigate emissions between 57 and 73% and energy savings ranging between 60 and 80%.
	Cold sintering	This process produces dense ceramic materials below 200 ◦C, therefore reducing the energy intensity. This technique uses a transitory, often liquid, phase to enable mass transfer to make denser ceramics employing uniaxial pressure. This transitory phase often evaporates in the cold sintering process, delivering densification by solution precipitation.	N.A.
	'Hybridedroger voor keramiek' (hybrid dryer)	What differentiates this technique from regular drying (drying chambers or tunnel dryers) is that two drying phases are applied in two drying chambers instead of only one. First, aerothermal drying is implemented using significant quantities of air. This is followed by semi-steam drying, which dries the product with air, high temperature and humidity.	Heating requirement decreases from 4 to 10 GJ/t to about 3 GJ/t. Delivering energy efficiency improvements of around 25%
	Optimization of the recirculation of drying air	Improving ventilation techniques to control main parameters such as temperature, humidity, and flow rate increases the efficiency of the hot-air dryer.	This technique can deliver energy savings of 25%.
	Pulsed hot air	Periodically interrupting the airflow permits the use of higher drying air temperatures. This technique gives enough time for the moisture to move from the centroid to the surface. Compared with a classic roller dryer, pulsed hot air is 40 min faster.	By using a pulse firing system, the ceramics industry can achieve savings of up to 30% compared with other traditional systems.



	High-efficiency burners	New high efficient burners allow preheating the combustion air with exhaust gases (e.g., self-recuperative and regenerative burners). These burners can substitute old ones in ceramic tunnel and/or roller kilns to reduce fuel consumption. This technique leads to firing efficiency improvement of about 10%; fuel savings ranging from 25 to 30% in self-recuperative burners and around 50–60% in regenerative burners.	This technology can generate energy savings of up to 15% regarding hot air recycling solutions.
	Airless drying	The main advantage of this technique is that the steam delivers higher specific heat and thermal conductivity relative to air. This allows improving heat transfer while reducing the risk of explosion by avoiding secondary contamination.	This technology leads to savings in thermal energy of 20–50% and significant reductions in the drying time.
	Integral thermal process	This technique optimises the firing process of tiles, and it involves supplying the exact amount of heat during each firing stage. The improved control leads to significant reductions in the firing time compared to fast roller kilns.	N.A.
	Fast-firing	Applying fast-fire cycles instead of utilising conventional kilns leads to reductions in the firing temperature of up to 50 ◦C.	This technique leads to reducing CO2 emissions by 25%.
	Inertizing	This method applies to tiles production. After the pressing stage, there is no drying, instead, a fast stage of drying–firing to a maximum temperature of about 900 ◦C is employed instead. This process lasts between 10 and 15 min depending on the thickness of the tile.	Applying this process leads to energy savings of up to 40%.
	Hot air recycling as combustion air in the kiln	The hot air from the cooling zone of a kiln could be utilized as preheated combustion air in the combustion chamber. This technique triggers a reaction where the thermal shock produced by high-temperature airflow reduces the mixture of hot air and air at ambient temperature. Fuels savings range from 15 to 30%.	This technique deliver fuels savings ranging from 15 to 30%.

	Optimization of the kiln charge	Optimising the firing surface area in roller kilns and the working charge in tunnel kilns improves the kiln's efficiency. This practice leads to lowering the energy end-use per unit of the processed product since less energy is required to raise the kiln's car temperature.	N.A.
	Extended tunnel kilns	Extending the tunnel kiln by 30–50% allow bricks to dry without employing cool air. Thus, making the tunnel kiln more energy efficient. This approach also enables that the drying process is decoupled from the firing kiln, leading to significant energy savings.	Applying this approach can lead to energy savings of up to 30%
	Kiln cars and furniture with low thermal mass	The use of low thermal mass in kiln cars helps in reducing the thermal energy requirement for the heating of supporting refractories. This technique reduces running costs, repairs, and maintenance.	This technique leads to fuel savings of up to 70%.
	Vertical Shift Brick Kiln	With this technique, green bricks are loaded on the top platform and move slowly towards the central firing zone. This allows the fresh air coming from below to cool the fired bricks prior to unloading. The kiln operates as a countercurrent heat exchanger, with heat transfer occurring between the upward moving air (continuous flow) and downward moving bricks (intermittent movement). Because of its fairly short firing period of about 24 h, the green brick ought to be suitable to resist fast heating and cooling to deliver high quality bricks.	N.A.
	Replacing conventional Hot Face Kyanite refractories with Ultralite ones	Replacing Hot Face Kyanite refractories with a density of 1100 kg/m3 with Ultralite™ can reduce the weight and heat absorption of the kiln car furniture.	This measure can lead to energy savings of 36,865 m3 N G/year and reductions of CO_2 of 77 t CO_2eq/year.
	Optimization of combustion efficiency	Installing an O2 sensor at the furnace exhaust for combustion air provides continuous feedback of percentages of O2. Having this information can help regulate combustion airflow to maintain an ideal combustion condition automatically.	Energy saving can reach up to 19,782 m3 NG yearly and could mitigate 41.344 CO_2 emissions each year.

	Pressure Casting (plasterless)	This technique supplies casting benches with casting slips under pressure. The resin or mould-plastic is employed as a filter instead of waiting for the water to be absorbed. The water in the casting slip is removed through the plastic/resin mould porosity, reducing the casting time. With this approach, energy savings are guaranteed due to the elimination of mould drying before reuse.	N.A.
Options for extractions of raw materials and alternatives to replace ceramics	Optimization of raw materials	Locally provided raw materials mitigate emissions from long distance transportation. Ceramic fibres and low thermal mass materials use new formulas that require less heating during the firing process. Utilising broken ware lead to energy savings and contribute to resource efficiency.	This approach could lead to up to 20% of energy savings.
	Incorporating new materials to improve the ceramics' design	New material compositions, for example, incorporating poreforming agents (such as carbon nanotubes) and through the incorporation of residues to produce thermal energy can lead to energy savings in the drying stage and improve material porosity leading to water savings.	This approach leads to up to 20% in energy savings
	Using low carbonate clay for yellow bricks in heavy clay subsector	In this approach, clay could be employed for the production of yellow bricks. The manufacturing process implementing low carbonate clay with colourant mitigates this emission.	This approach can mitigate emissions by up to 10%.
	Recycling sludge from other industries	Utilising such material in the manufacturing of ceramics can lead not only save raw materials but, in other cases, can also lead to reducing firing temperatures and therefore mitigate GHG emissions. For instance, adding 10%wt of paper sludge results in economic savings of 3% and lowers firing temperature to 750 ◦C.	This formula can lead to energy savings of up to 20%.
Ceramics waste and recycling in	Reuse of waste from operations	Broken pieces of ceramics or waste emerging from grinding and the decorating and glazing operations could be added as a raw material in the subsequent batches. Implementing this approach reduces landfills occupation, mitigate emissions and save resources.	N.A.

	Ceramics waste	Instead of being disposed of in landfills, avoid waste generation and reliance on virgin materials from overseas, ceramics waste can be employed in diverse materials for the construction industry.	N.A.

Notes: N.A. stands for Not Applicable.

Literature also indicates that for the economy segments that are not easily electrified, CCS could be another technology to help mitigate emissions [5]. However, such approach could be erroneous. Individual ceramic sites are not considered big enough to justify having dedicated CCS infrastructure. More, if we consider the high costs that emanate from transportation, development and operation of storage sites that CCS entails. Ceramic manufacturers are often located in isolated or rural areas, so carbon capture emissions systems do not seem like a feasible investment option. Carbon capture technologies may not be appropriate for commercial application in the ceramic industry [5].

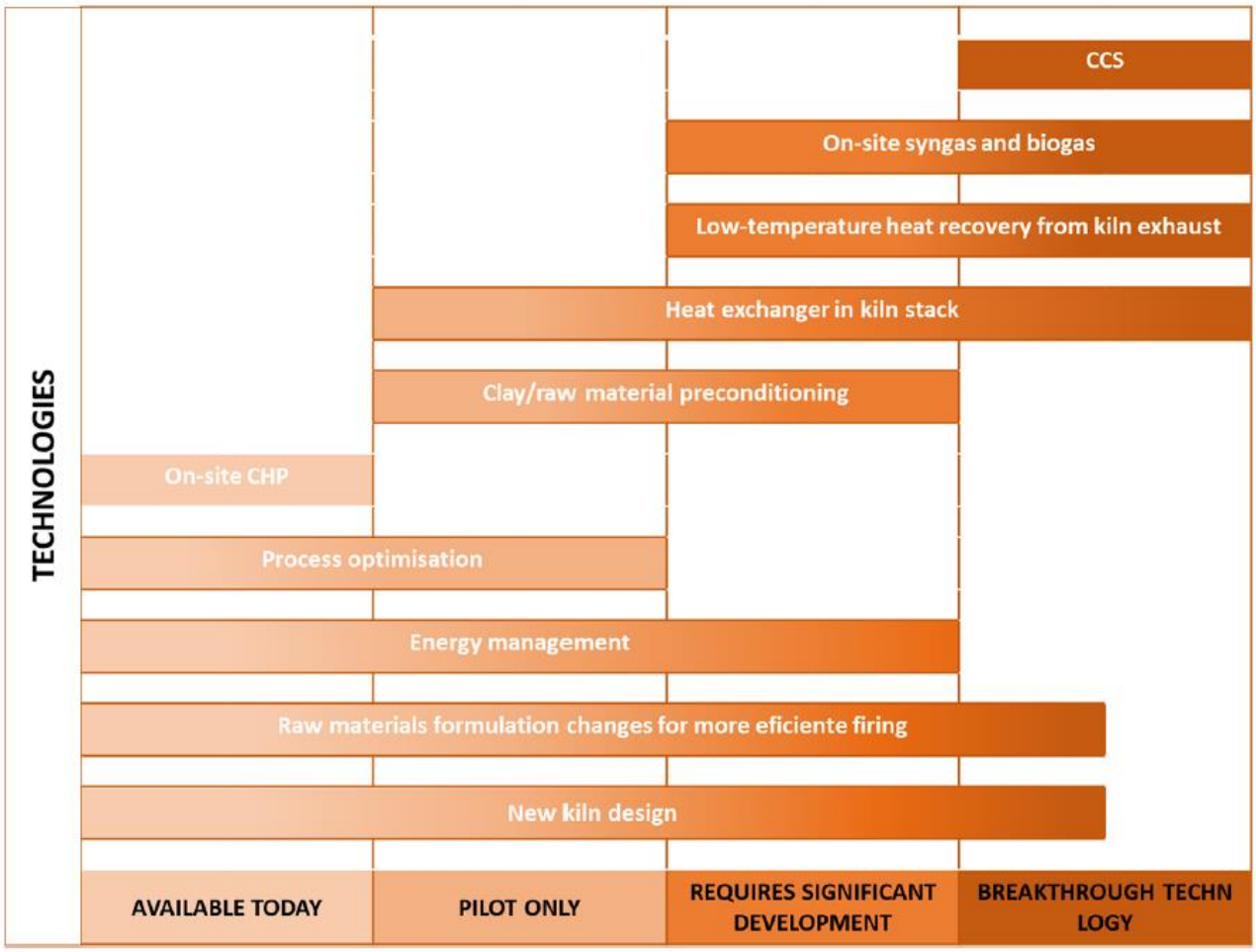


Figure 17 – Roadmap to decarbonise the ceramics industry. Note: CHP = combined heat and power. CCS = carbon capture and storage. Taken from the original source [5].

2.11 Barriers and risks facing the decarbonization of the ceramics

Although there are many options for the decarbonization of the ceramics industry, some barriers (any factor impeding technology adoption) and risks (any negative outcome to technology adoption) prevent their achievement [5].

Table 12 – Barriers and risks facing the decarbonization of the ceramics. Source [5].

A	• Manufacturing ceramics entails high heating requirements, currently provided with fossil fuels that cannot be easily replaced with existing technologies. • The objectives for the European ceramic industry are extremely demanding and unreachable with existing policies and technologies. • Installing electric driers and kilns will not be enough to achieve the industrial EU targets on CO_2 emissions. • Electric kilns have not yet been implemented on a continuous and large scale. • Viability of applying electric kilns in large-scale ceramic manufacturing plants remains debatable. • Since the industry is sensitive to fluctuating electricity prices, in tandem with unproven large-deployment of high-temperature heat electrification technologies (e.g. electric kilns), there is an uncertain investment environment to advance the electrification of the industry. • A large-scale continuous electric kiln might operate differently than a kiln heated by gas combustion. • Geographical location and the fact that many manufacturing sites are widely dispersed also influence technologies' deployment. • Near-term hydrogen areas adoption is most likely to occur in industrial clusters where hydrogen production, distribution, and use are economically feasible • Ceramic plant's locations often have a rather limited installed grid capacity • Problems around infrastructure capacity when employing electrification options such as electric drying and firing or assisted microwave for drying and firing may occur • For local and/or small ceramic producers, when the commercial technology is developed and supplied, resistance or even rejection of new technologies may occur due to the economic, business process and technical barriers that new technology adoption involves. • Regarding hydrogen utilisation, some technical unknowns remain, including i) lower volumetric energy content than natural gas and a flame with lower radiation heat transfer than natural gas; ii) potential increase of NOx emissions; iii) safety-related considerations, particularly for storage; iv) costs; v) manufacturing infrastructure that may be incompatible with hydrogen. • Biomass cost and supply represent serious issues for the decarbonization of this industry according to the Department of Energy and Climate Change (DECC).



	• A full switch to bio-based fuels is not possible without novel kilns that many industries do not have yet. • There are also relevant issues regarding distribution barriers and quality requirements, affecting, in consequence, the availability of biofuels that the ceramic industry would require. • Imported technologies (e.g. from China or the EU) are not easily adapted to local contexts.
B	• Ceramic manufacturers often give low priority to more efficient energy practices as well as sustainability awareness • Lack of cost-benefit and viability analyses of efficient technologies, impedes the investments to deploy more sustainable measures. • Companies delay cost-effective actions not because energy-related investments are perceived as less important but because the selection of these projects is often based on an expected rate of return. • DECC, identified that the absence of technical knowledge and capacity to identify novel technologies and measures to mitigate emissions represent another key barrier. • There is a recurrent lack of information about more energy-efficient practices for small and medium ceramic producers. • Long lifetime of technologies operating in the ceramics industry. • The lifespan of a kiln can be up to 40 years and accounts for significant capital investment; therefore, it is not economically feasible to replace them regularly. • Given the kilns' lifetime, there will only be one or, at most, two replacement cycles between now and 2050 and hence limited opportunities for equipment improvements. • The wave of green investments in this industry took place during the late 1990s. Thus, companies are not willing to make further investments in such a short period. • Unexpected interruptions of energy supply could generate significant damages to continuous kilns, to the point that the factory could shut down for months and augment their production costs per unit. • Increasing and volatile gas and electricity prices deter investments in more energy-efficient measures.
C	• Unwillingness to invest in energy-efficient measures with payback times above 3–5 years. • Absence from government financial schemes along with a lack of grants to incentivise the adoption of energy-efficient technologies. • Until sufficient financial support from the government is provided, the ceramic industry will not transition towards a zero-carbon path. • Lack of incentives and regulations to promote less polluting technologies for brick operators.



D	• Cogeneration grounded on a beneficial heat demand in the internal energy market[11]. • Enhance and extend the GHG trading scheme of emissions allowance from the EU[12]. • Addressing industrial emissions (integrated pollution prevention and control)[13]. • Sectors considered to be exposed to risks of carbon leakage[14].

A) Manufacturing, managerial and infrastructural concerns; **B)** Lack of information, knowledge, and skills; **C)** Financial and economic disincentives; and **D)** Regulations to mitigate emissions.

[11] Directive 2004/8/EC of the European Parliament and of the Council of February 11, 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market
[12] Directive 2009/29/EC of the European Parliament and of the Council of April 23, 2009 amending Directive 2003/ 87/EC on the establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council.
[13] Directive 2010/75/EU of the European Parliament and of the Council of November 24, 2010 on the on industrial emissions (integrated pollution prevention and control).
[14] Commission Decision of December 24, 2009 determining, pursuant to Directive 2003/87/EC of the European Parliament and of the Council.



3 Bricks and roof tiles

3.1 Introduction

The clay brick and tile industry is an extractive industry relying on natural resources for its raw materials. The process can be handled in a sustainable manner with restoration following extraction. It is vital for the industry that there is long term mineral planning to ensure security of supply and thereby encourage investment. The location of brickworks, tileworks and their quarries in rural and semi-rural areas has allowed the industry to provide long-term, stable employment to small neighbourhoods and communities. An established relationship between manufacturer and community can fulfil many of the sustainability criteria considered under social progress [10].

The European brick and tile industry represents more than 700 companies, from SMEs to large international groups, which employ around 50,000 people across Europe and generate a production value of around €5.5 billion. In Europe there are over 1,300 production sites located near quarries which provide local jobs and keep transport emissions low.

Over the last decades, the sector has invested heavily in product and process innovations that have revolutionised the manufacturing process and delivered modern building solutions. This technological progress has profoundly modified the functioning of brick and roof tile plants. Today kilns are fully automated and heat recovery systems optimise the overall energy efficiency of the plant. Futhermore, modern process technology ensures that the environmental impact is minimal.

Clay building products are perfectly suited to construction. Thanks to their versatility and unique technical and aesthetic characteristics, they have shaped the built environment for centuries and offer innovative solutions for the buildings of tomorrow.

Clay bricks, blocks, roof tiles and pavers are durable, affordable and provide comfortable, safe and healthy homes to millions of people. Furthermore, they combine traditional architectural heritage with innovative and future-oriented construction methods. Last but not least, clay products offer valuable solutions to save energy and reduce greenhouse gas emissions in the building sector[15].

3.2 Production process

The technological progress made in the last decades profoundly modified the look of brick and roof tile plants. Today, kilns are fully automated and heat recovery systems optimise the overall energy efficiency. Furthermore, modern process technology ensures that the environmental impact is minimal. Research and development projects are looking into those elements which will shape the

[15] http://www.tiles-bricks.eu/industry (accessed on April the 2022)



plants of tomorrow, such as alternative sources of energy, new energy efficiency technologies, recycling of final products and the use of recycled raw materials.

After extraction from quarries, the clay raw material is laid out in order to obtain a homogeneous mixture. Several stages are involved in preparing the clay. It is stockpiled, then crushed to attain the required grain size and then stockpiled again for several days or even months. Before processing, the moisture content is controlled and it may be necessary to add water to obtain the right consistency for forming. Materials such as sawdust or residue of paper industry can be added to increase the porosity of the final product.

For bricks, the clay is extruded or moulded to obtain the shape required and then cut to size. In roof tilemaking, the clay can undergo a two-stage process, the second of which may occur after extrusion, depending on the roof tile being manufactured. For example, for interlocking tiles, the extruded clay is pressed between two moulds. The formed clay is dried in order to reduce its moisture content and then loaded into kilns for firing. Drying and firing are the most energy-intensive steps of the production process and the industry has made major investments to reduce energy consumption and CO_2 emissions. The key improvements are linked to the development of better designed driers and kilns, the recovery of excess heat from kilns, the use of high-speed burners and the automated control of drying and firing regimes. Further emissions reductions have been achieved through the improvement of the energy mix. In most cases, natural gas has replaced more CO_2-intensive fossil fuels (like coal, oil and petcoke) and renewable energy sources like biomass are used when available and economically viable.

When this is completed and the products have cooled, they are packed ready for dispatch. Throughout all stages of production, the process is subject to rigorous quality control.



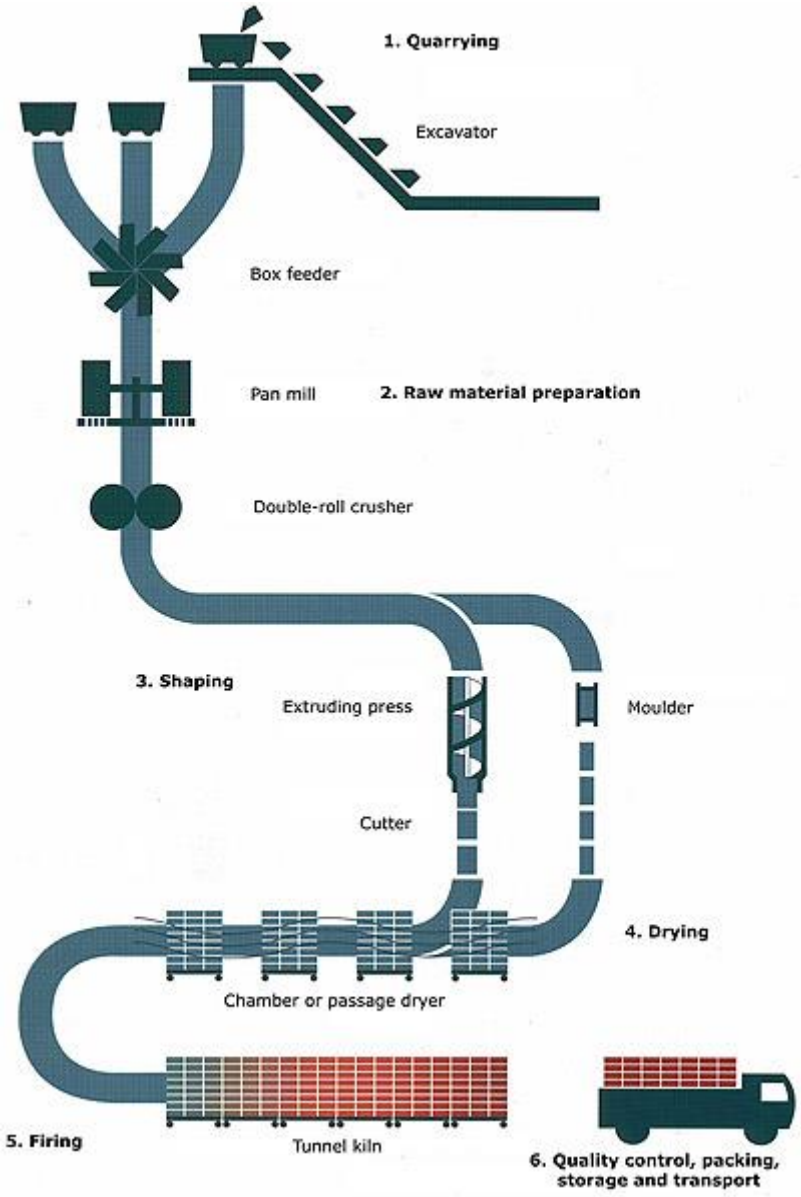


Figure 18 – Example of production of extruded bricks and handmade bricks

3.3 Energy consumption and GHG emissions

The energy consumed during the manufacture of clay products is primarily that used in forming, drying and firing. Since energy costs are an important part of total production costs (up to 30%), the clay industry has always closely monitored its energy usage. Ecology and economy are often linked and the European brick and tile industry has not waited for statutory regulation before investing in better energy efficiency. Firing is responsible for the exceptionally long life of this sector's products. Moreover, some products are designed to save energy when incorporated into buildings and the

thermal performance of such products has increased significantly over the last few years.

Natural gas, LPG and fuel oil are used for most drying and firing operations, but solids fuels and electricity are also sometimes used, as is gas from landfills. Natural gas is increasingly used in factories. This fossil energy produces the least carbon dioxide-CO_2 (57 kg CO_2 / GJ as opposed to fuel oil which produces 75 kg CO_2 / GJ).

Table 13 – Development of the percentage of various fuels used (thermal energy) clay brick & roof-tile industry. Source: [10].

Development of the Percentage of Various Fuels Used (Thermal Energy)
Clay Brick & Roof-tile Industry

	COAL					OIL					NATURAL GAS				
	1960	1975	1990	1995	2001	1960	1975	1990	1995	2001	1960	1975	1990	1995	2001
AUT			2	0	0*			20	19	15*			78	81	85*
BEL	83	4	10	4	2**	17	40	7	6	2**	0	56	83	90	96**
GER	77	5	3	3		20	76	17	15		3	19	80	82	
DEN	68	11	5	4		32	89	9	9		0	0	86	87	
FRA		4	15	0			56	9	5			40	76	95	
ITA			0	2	0*			49	19	10*			51	79	90*
NED	49	2	2	1		51	1	1	0		0	97	97	99	
ESP	30	10	0	0		50	65	71	67		20	25	29	33	
UK		50	11	4	3		14	4	2	1		36	85	94	96
HUN	94	60	26	15		6	8	0	0		0	32	74	85	
CH			1	0	0			63	51	47			36	49	53

* 2000
** 2002
Data listed in this table are based on information provided by the National federations and associations. (source : TBE)

3.4 Energy efficiency and decarbonisation innovations

Throughout the industry, the widespread change to gaseous fuels and improvements in drying, kiln technology and control have resulted in a progressive reduction in energy use and a marked reduction in emissions.

The primary process improvements are:

• improved design of dryers and kilns

• computer control of drying and firing regimes

• recovery of excess heat from kilns (mainly hot air from cooling zones of kilns ducted to dryers)

• product modifications.

Table 14 – Specific Energy Consumption (GJ/tonne) – Brick & Roof-tile Industry. Source: [10].

Specific Energy Consumption (GJ/tonne) – Brick & Roof-tile Industry

	1980	1985	1990	1995	2001	Reduction %[6]
AUSTRIA	2.38	2.09	1.71	1.72	1.65*	28
BELGIUM	3.30[2]	2.73[2]	2.16[2]	2.37[3]	2.23[3] **	32
GERMANY	2.43	2.31	1.93	1.63		33
DENMARK	2.73	- [1]	2.41	2.67		2
SPAIN	2.38	2.29	2.24	2.18		8
FRANCE	2.87	2.62	2.76	2.61		9
ITALY	2.8	2.6	2.1	1.9	1.9	32
THE NETHERLANDS	3.63	2.93	2.86	2.7		26
UNITED KINGDOM	1.1[4] 3.58[5]	1.01[4] 3.26[5]	0.84[4] 2.97[5]	0.83[4] 2.80[5]	2.42[4] 1.4[5]	25[4] 22[5]
SWITZERLAND	- [1]	2.55	2.62	2.53	2.32	1

* 2000
** 2002
[1] not available
[2] only bricks - data based on NIS
[3] clay bricks and roof tiles - based on data provided by the federation
[4] UK Fletton & [5] UK Non-Fletton / data for 1980 not available - data shown for 1984. The Fletton Industry cannot be compared to the previous figures. There have been large production changes to the output types at the 3 remaining fletton sites.
[6] 1995/1980 but 1995/1985 when the 1980 consumption data are not available - for Belgium ratio 1980/1990

4 Wall and floor tiles

4.1 Introduction

Ceramic tiles are flat, slim pieces made from clay, silica, fluxing agents, stains and other raw materials. They are normally used as coverings for floors, walls and façades. Red or white firing clays may be used for the tile body. Floor and wall tiles are normally impermeable ceramic pieces made from a clay body with a glass coating (ceramic glazes). The vast range of ceramic tile products currently available on the market is conditioned by their multiple uses in both architecture and interior design. The products and their characteristics vary in accordance with the use they are put to[16].
Different processes are used for wall and floor tiles due to the differences in requirements (e.g. frost resistance for outdoor tiles) which requires specific raw materials and extra process steps. This results in two main types of ceramic tiles which both use raw materials like clay, sand, marl, felspar, broken ware and recycled tiles. The first type are pottery tiles that are mainly used for wall tiles. The second type, 'porcelain tiles', are tougher than pottery tiles and have a higher wear resistance. In addition, porcelain tiles are frost resistant, which pottery tiles are not. This makes porcelain tiles applicable to both walls and floors, including high traffic zones like shopping malls [2].

4.2 Production process

Figure 19 shows the manufacturing processes for floor and wall tiles. The main difference between the two processes is that wall tiles require a double firing process and glazing. Floor tiles only require fast firing to receive full sintering.

Preparation and shaping

The raw materials are milled and mixed to reach a homogenized substance. Floor tiles need a different bottom and top layer, so two substances are created for that product.

Drying

To decrease the water content the particle size of the substances are reduced even more by removing embedded water, for which spray drying is applied. This method, taking place before the shaping process, sprays hot air through the substance. As a result, granulation takes place: fine droplets are formed and form highly uniform granules that facilitate accurate filling of the pressing dies. The moisture content decreases from approx. 30% to 6% and the required temperature within

[16] https://www.ascer.es (accessed on April, 2022)

the spray dryer is 350-450 °C, requiring an energy consumption of 1.1 – 2.2 GJ/t. The shaping of floor and wall tiles, which for floor tiles is in fact adding two layers of substance together, is done by isostatic pressing with a pressure of 400 tonnes per 30x30 cm. After shaping the tiles, the second step of drying is applied to further decrease the water content. This process is done with a temperature of 90 °C. The drying duration per batch of tiles is three hours and the residual water content is less than 1 percent [2].

Firing and subsequent treatment

Firing takes place in a fast-firing roller kiln (also named 'modern roller hearth kiln') with a temperature of up to 1230 °C to ensure the tiles become fully sintered. The tiles are horizontally placed on ceramic rollers instead of the old method where tiles are stacked vertically in tunnel kilns. Wall tiles have an extra process step: biscuit firing and glazing. This is necessary for optimal colouring and shining properties. Whereas floor tiles are immediately fired at a temperature of 1230 °C, wall tiles are first biscuit fired at a temperature of 1100 °C. At the same time the glazing material is prepared, which is a glassy substance that consists of melted feldspars. After the wall tiles are biscuit fired, glazing is applied by moving the tiles through a curtain of glazing. When the glazing has dried, the tiles are another time fired at a temperature of 1100 °C. After cooling down, the dimensions of the tiles are adjusted if required and some types of floor tiles could be ground or polished, recycling any material if possible. Finally, the tiles are packaged and stored at one of the warehouses.



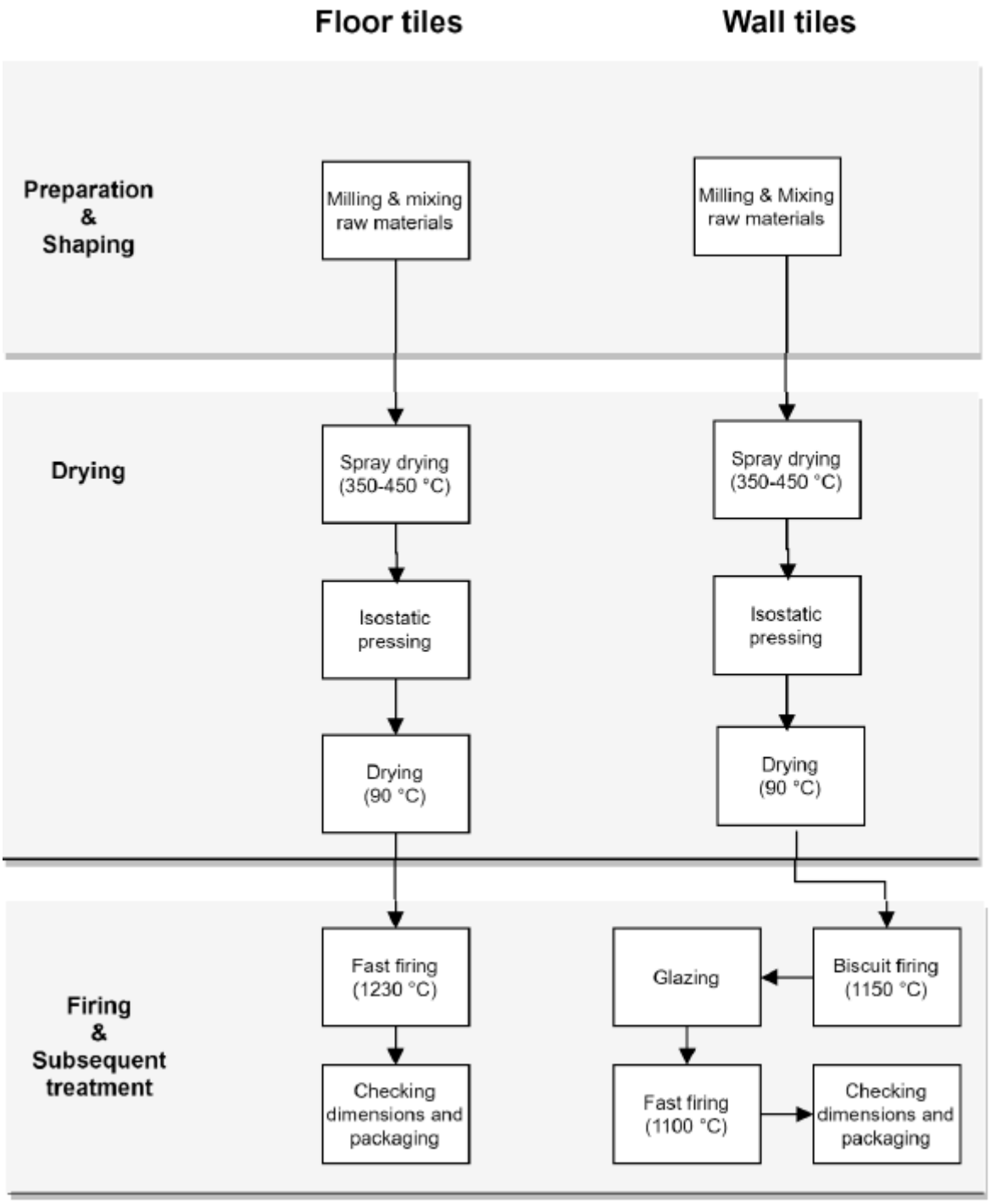


Figure 19 – Example of production of wall and floor tiles. Source [2].

4.2.1 Material, energy and CO_2 emissions flows

Figure 20 and Figure 21 show the material, energy and CO_2 emissions flow diagram of floor and wall tiles using the Dutch ceramics sector as an example [2].

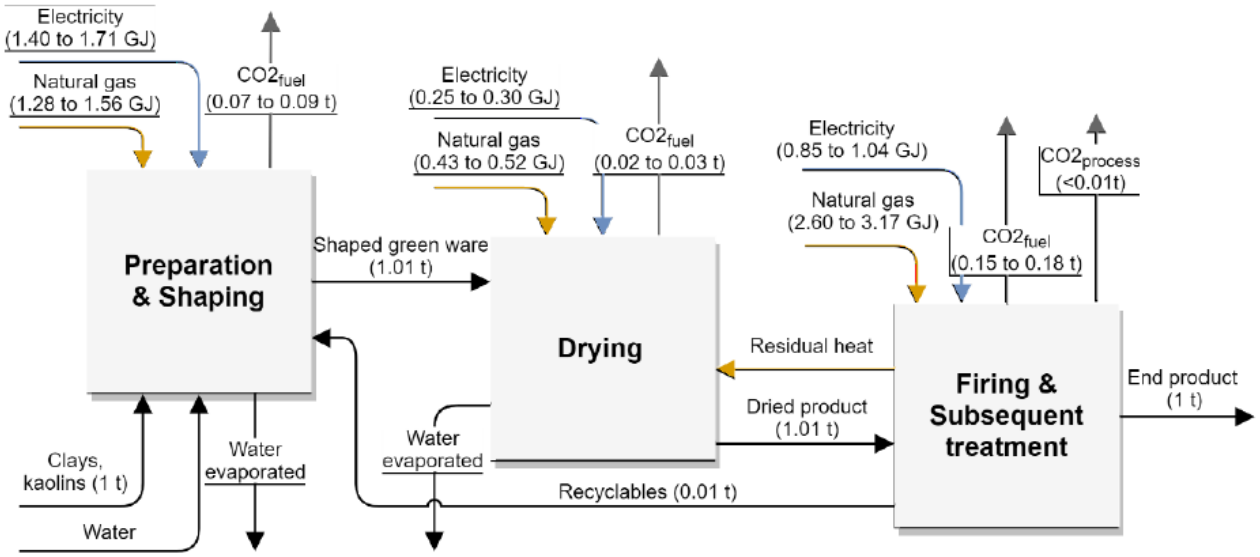


Figure 20 – Flow diagram of the manufacturing process of floor tiles, including material, energy and CO2 emissions flows. Source [2].

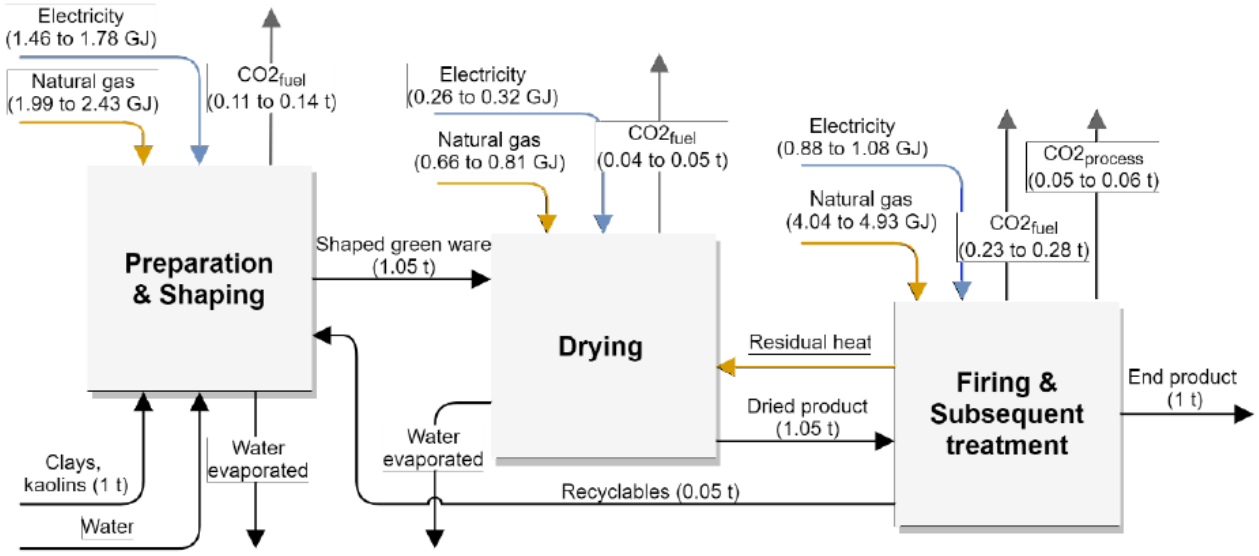


Figure 21 – Flow diagram of the manufacturing process of wall tiles, including material, energy and CO2 emissions flows. Source [2].

4.3 Energy consumption and GHG emissions

Figure 17 and Figure 18 show the material, energy and CO_2 emissions flow diagram of floor and wall tiles, respectively. The calculation method of the values in the flow diagrams and used sources are provided in Appendix A. The amount of residual heat extracted from the firing section used for drying

could not be determined. Note that the calculations use European data (EC, 2007). As the energy consumption of the Dutch ceramic mills may deviate, the given values should be treated as indicative values.

5 Refractory products

5.1 Introduction

Refractories are materials that provide linings for high-temperature furnaces and other processing units. Refractories must be able to withstand physical wear, high temperatures (above 538ºC), and corrosion by chemical agents. There are two general classifications of refractories: clay and nonclay [11]. Clay refractories are produced from fire clay (hydrous silicates of aluminum) and alumina (57 to 87.5 percent). Other clay minerals used in the production of refractories include kaolin, bentonite, ball clay, and common clay. Nonclay refractories are produced from a composition of alumina (<87.5 percent), mullite, chromite, magnesite, silica, silicon carbide, zircon, and other nonclays. Refractories are produced in two basic forms: preshaped objects and unformed compositions in granulated or plastic forms. The preformed products are called bricks and shapes [11]. These products are used to form the walls, arches, and floor tiles of various high-temperature process equipment. Unformed compositions include mortars, gunning mixes, castables (refractory concretes), ramming mixes, and plastics. These products are then cured to form a monolithic, internal structure after application [11].

Refractory products are a vital element in all high-temperature processes, such as metals making, the production of cement, petrochemical processes, glass and ceramics. Without refractories there would be no cars, no planes, no trains, no gas or electricity and we would be eating from wooden plates and living in mud-brick huts[17][18].

Refractories are essential for the production of steel, iron, aluminium, cement, glass, ceramics, and are also used in incinerators, oil refineries, coal -fired power stations and many other industrial sectors where temperatures over around 800°C are encountered (*Table 15*). Refractories primarily serve to contain high temperature materials during processing and provide heal insulation. Consequently, low thermal conductivity and resistance to erosion, corrosion and stability al high temperatures are desirable properties in most cases [12].

The steel industry is the most important customer for the refractories industry, accounting for more than 55% of all refractories sold in Europe. All high- temperature steel making processing units

[17] http://www.pre.eu (accessed on April, 2022)
[18] https://youtu.be/oxbfNHJ9vyM

incorporate refractories of some kind. In ladles and tundishes and some other processing units, the conditions are so severe that the linings need replacing or repairing every few days and, in extreme cases, every few hours. These consumable refractory items make up almost two thirds of the refractories demand in the iron and steel industry worldwide. Steelmakers are acutely aware of the risks of incorporating non-metallic inclusions from any source into steel; therefore, the quality and integrity of refractories for this application are paramount [12].

Cement clinker output in Western Europe stood at about 192 million tonnes in 2002, with most of the growth in Spain and Portugal. In Western Europe, cement production methods now usually incorporate preheating or precalcination units, thereby cutting down on consumption of both energy and refractories. Cement precalciners use aluminosilicate bricks and monolithics; the sintering and transition zones of the cement rotary kilns require magnesia-spinel bricks and some dolomite bricks. Usage of chrome-containing bricks has declined severely due to environmental factors; they have been replaced, to a large extent, by bricks based on spinet [12].

Table 15 – Example of demand for refractory materials by industrial sector in 2022 in western Europe. Source [12].

Thousand tonnes	Industrial sector
1460	Steel production and handling
997	Non-ferrous metals, power generation, incinerators, petrochemicals, foundries, other
300	Iron and coke production and handling
260	Ceramics
240	Cement
90	Glass
3347	**Total**

5.2 Production process

Refractories are materials that provide linings for high-temperature furnaces and other processing units. Refractories must be able to withstand physical wear, high temperatures (above 538°C), and corrosion by chemical agents. There are two general classifications of refractories, clay and nonclay.



Clay refractories are produced from fireclay (hydrous silicates of aluminum) and alumina (57 to 88%). Other clay minerals used in the production of refractories include kaolin, bentonite, ball clay, and common clay. Nonclay refractories are produced from a composition of alumina (<88%), mullite, chromite, magnesite, silica, silicon carbide, zircon, and other nonclays [11].

Refractories are produced in two basic forms, formed objects, and unformed granulated or plastic compositions. The preformed products are called bricks and shapes. These products are used to form the walls, arches, and floor tiles of various high-temperature process equipment. Unformed compositions include mortars, gunning mixes, castables (refractory concretes), ramming mixes, and plastics. These products are cured in place to form a monolithic, internal structure after application [11].

Refractory manufacturing involves four processes: raw material processing, forming, firing, and final processing. Figure 22 illustrates the refractory manufacturing process. Raw material processing consists of crushing and grinding raw materials, followed if necessary by size classification and raw materials calcining and drying. The processed raw material then may be dry-mixed with other minerals and chemical compounds, packaged, and shipped as product. All of these processes are not required for some refractory products [11].

Forming consists of mixing the raw materials and forming them into the desired shapes. This process frequently occurs under wet or moist conditions. Firing involves heating the refractory material to high temperatures in a periodic (batch) or continuous tunnel kiln to form the ceramic bond that gives the product its refractory properties. The final processing stage involves milling, grinding, and sandblasting of the finished product. This step keeps the product in correct shape and size after thermal expansion has occurred. For certain products, final processing may also include product impregnation with tar and pitch, and final packaging [11].

Two other types of refractory processes also warrant discussion. The first is production of fused products. This process involves using an electric arc furnace to melt the refractory raw materials, then pouring the melted materials into sand-forming molds. Another type of refractory process is ceramic fiber production. In this process, calcined kaolin is melted in an electric arc furnace. The molten clay is either fiberized in a blowchamber with a centrifuge device or is dropped into an air jet and immediately blown into fine strands. After the blowchamber, the ceramic fiber may then be conveyed to an oven for curing, which adds structural rigidity to the fibers. During the curing process, oils are used to lubricate both the fibers and the machinery used to handle and form the fibers. The production of ceramic fiber for refractory material is very similar to the production of mineral wool [11].



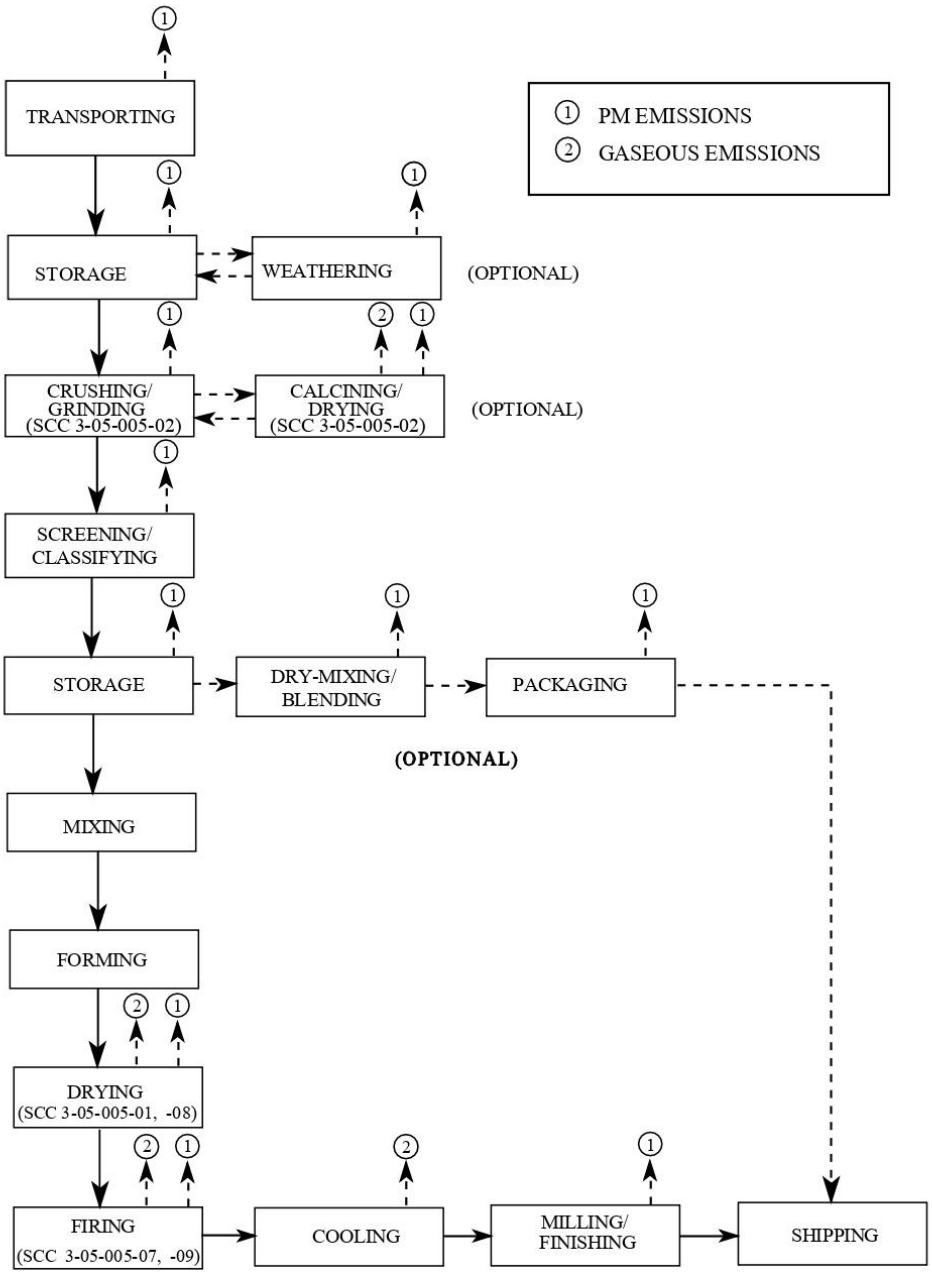


Figure 22 – Refractory manufacturing process flow diagram. Source: [11].

5.2.1 Material, energy and CO_2 emissions flows

First the raw material is milled to predefined particle sizes, then additives are added together and mixed to obtain a homogenized material. In total, 7 to 10 different types of materials and ingredients are used as raw material input. The shaping process is applied by mechanical pressing in moulds and both the drying and firing takes place in tunnel kilns. Both the drying and firing process use natural gas. Drying requires a temperature of 100 °C and firing a temperature of 1700 °C. After the

firing process, which takes 2 to 3 days, the refractory product is cooled down and given subsequent treatment based on the customers' requirements [2].

Figure 23 show the material, energy and CO_2 emissions flow diagram of refractory products using the Dutch ceramics sector as an example [2].

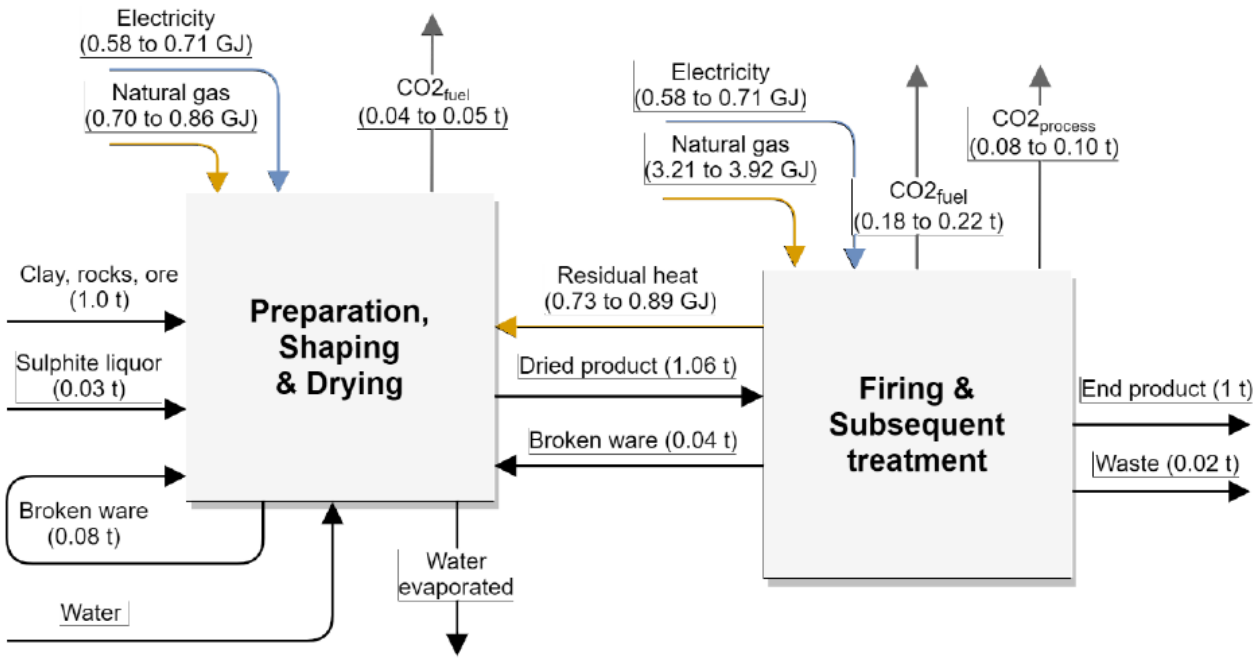


Figure 23 – Flow diagram of the manufacturing process of wall tiles, including material, energy and CO2 emissions flows. Source [2].

6 Technical ceramics

6.1 Introduction

Technical ceramics represent 9% of the total European production value within the sector (Figure 3). The first ceramics were the low-firing earthenwares that appeared some 10,000 years ago when humans had mastered the use of fire [13]. Those early potters used simple pit firing, for they lacked kilns (specially designed ovens) for firing their wares. Nonetheless, the production of those early, unsophisticated earthenwares was the starting point for the subsequent development of ceramics. Until perhaps 100 years ago, the word ceramics meant pottery; ceramic products were limited to tableware for everyday use, roofing tiles (see Section 2.1.2), clay pipe, and brick (see Section 2.1.1). The mass production of iron and steel, which began in the latter half of the nineteenth century, required the development of new refractory ceramics, entailing a shift from the use of conventional fireclays to refractory materials containing silica, alumina, chrome-magnesia, or magnesia. Without these advances in refractory materials, the production of steel and other metals could not have attained its present development [13].

Ceramics have made essential contributions in many other sectors of industrial society as well. For instance, the rapid production of textiles made of synthetic fibers has been made possible by the advent of thread guides of alumina and other ceramic materials. Bisque wares are used in biotechnology and in sewage disposal. They are just as much ceramic products as are teacups or flower pots for bonsai [13].

Today, ceramic products touch our lives in many ways. Pottery and porcelain vessels, glass, and cement are only among the more familiar. Their applications include the magnets in television sets, optical fibers for telecommunications, automobile spark plugs, and the insulators for Japan's high-speed trains. They are widely used in electronics, not only as magnets and as insulators, but also as heating elements and substrates for integrated circuits. As engineering ceramics, they appear in ceramic engines and cutting tools. In bioceramics, they are used for artificial teeth and bones [13].

6.2 Production process

Classification by methods of production like sintering and heating, their advantages and



disadvantages, and their applications are summarized in Figure 24.

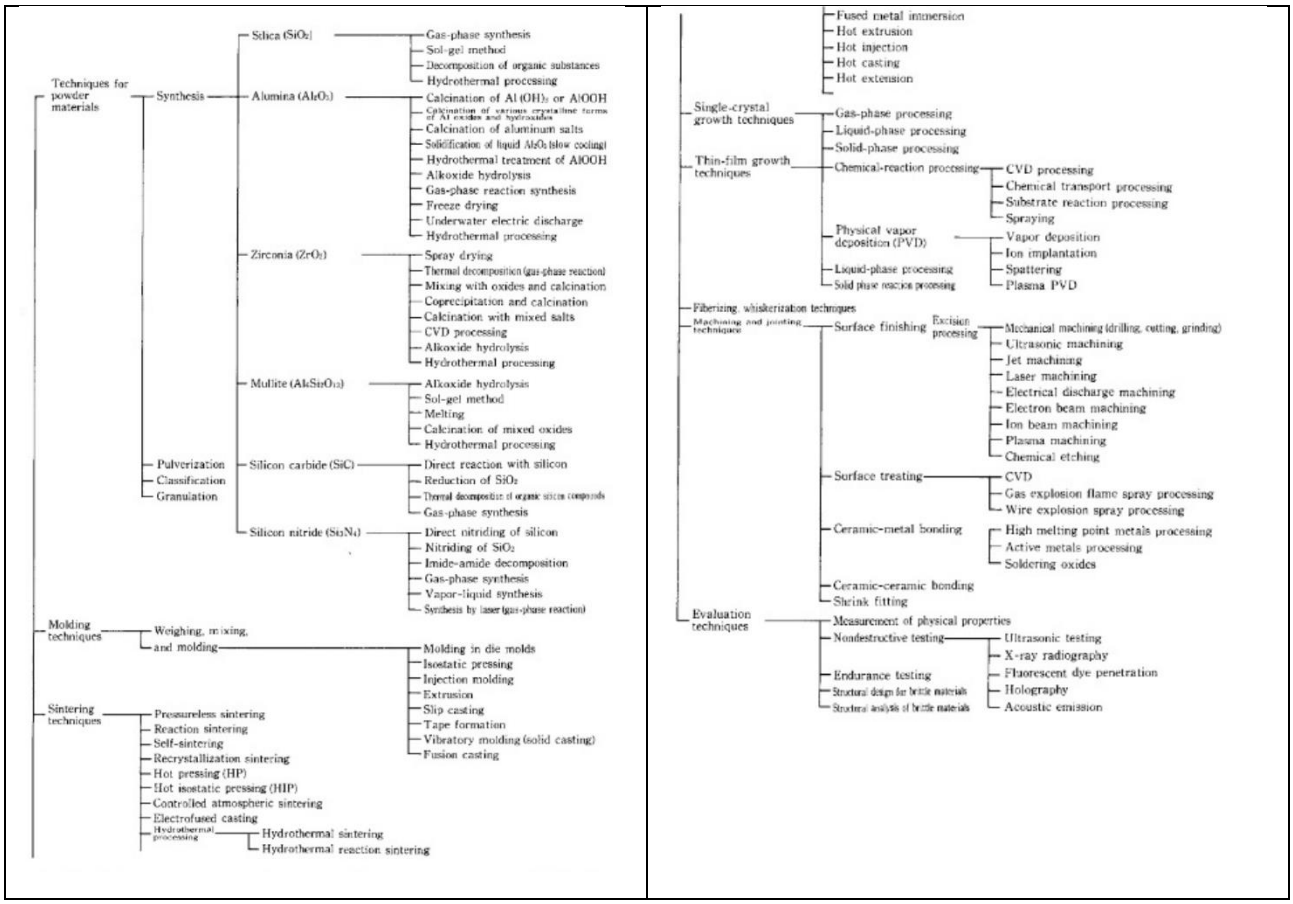


Figure 24 – Processing of advanced ceramics. Source: [13].

7 Conclusions

The EU ceramics industry is a world leader in producing high quality ceramic products. Most manufacturers are small and medium size enterprises. The sector provides over 338 thousand jobs and accounts for around €28 billion in product value. Ceramics production processes are energy intensive with the construction (bricks and roof tiles) sub-sector being the one where more energy resources are consumed. Overall, natural gas is the main energy source in kiln. In the process of firing and drying, natural gas consumption reaches approximately 85% of the whole of energy consumption in the manufacturing process. Electrical energy is used mainly for comminution, mixing and forming. It stands for approximately 15% of the energy consumption in the sector. According to the EU Emissions Trading System, total emissions from the EU ceramics sector amount to 19 million tonnes of CO_2 annually. Emissions can be broken down into three main categories: a) Fuel combustion for drying and heating process; b) Process emissions generated by mineralogical transformation of the clay; and c) Indirect emissions, mainly from electricity production. The transition to a competitive low-carbon and resource-efficient economy in 2050 represents a challenging target for the European ceramic industry. The 2050 emissions reduction targets are even more challenging for a capital-intensive sector with long investment cycles like ceramics. The EU ceramic sector has reduced its total emissions by around 33% since 1990. In the 2000s, by 45%. This has been possible by optimising processes, making production more efficient and by fuel substitution from solid fuel (mainly coal) to natural gas. To achieve carbon neutrality by 2050, the ceramics industry will nearly need 50k TJ each of green hydrogen, biogas, and green electricity. These amounts are not currently available to the industry. Their supply does not exclusively depend on the industry but on many factors, such as infrastructure and the right legal and policy framework. According to Cerame Unie the annual decarbonisation cost of the U sector will exceed €500 million by 2030. The annual costs will progressively grow to nearly 1 bn EUR per year in 2040 and will exceed 1.2 bn per year in 2050. The total accumulated costs until 2050 are estimated at around 27 bn EUR. Energy efficiency improvements have been made in the EU ceramic sector, resulting in more efficient kiln designs and drying techniques. The drying and firing process has become a continuous process (creating a stable energy demand). However, further decarbonisation is required to achieve net zero (fuel) CO_2 emissions. Relevant categories for further decarbonisation are fuel substitutions, process design, use of residual energy and CO_2 capture and storage (or utilisation).



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100% Renewable Energies for Energy Intensive Industries

Grant Agreement Nº 952936

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Lead Beneficiary: CERTH

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Abbreviations

Abbreviation	Definition
CO_2	Carbon dioxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
SDGs	Sustainable Development Goals
EII	Energy Intensive Industry
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
NAFTA	North American Free Trade Agreement
RE / RES	Renewable Energy / Renewable Energy Sources



1 Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe, focusing on the chemical and fertilizer industrial sector. The report aims to capture the current status of the chemical and fertilizers sector in Europe, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonisation.

Following this introduction, the report is divided in two chapters, the first one describes the chemical industry and the second one the fertilizer industry.

The report provides information on the current usage and importance, the production processes, the energy and GHG emission profile, as well as potential alternatives for mitigating their climate impact. Finally, it presents the overall challenges and barriers that the chemical and fertilizers sector faces and potential measures and solutions for a decarbonised future.

Regarding the chemical sector, which includes different industrials sector, the focus will be on fertilizer sector which is one of the basic subsectors of selected industries that RE4industry investigates.

The report is supplemented with four Annexes, which discuss the status of energy intensive industries in RE4Industry partner countries: Germany, Greece, Netherlands and Spain. Each Annex provides information regarding the main industries which are currently active in the sector, as well as any efforts and commitments undertaken regarding integration of renewable energy sources and decarbonisation in general.



2. Chemicals

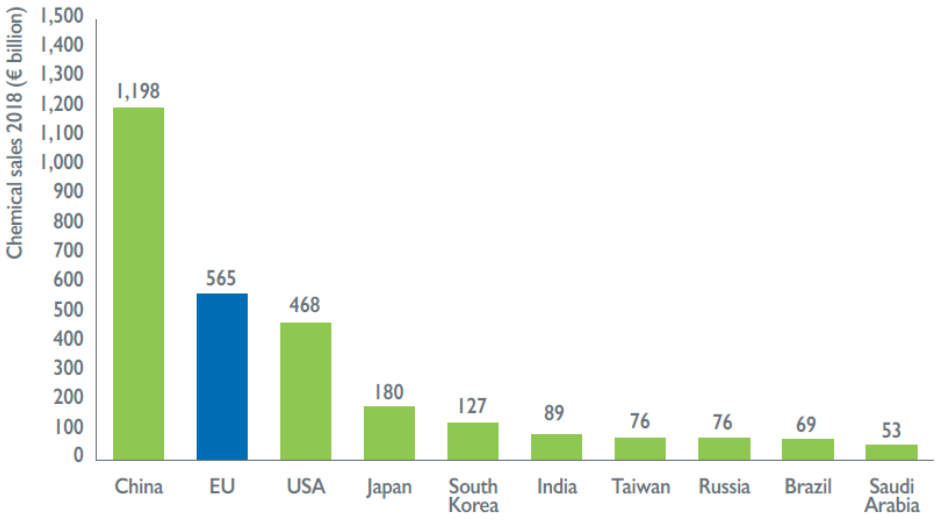
2.1 Introduction to EU chemical sector

Chemical products and technologies are used in almost every area of the world economy since they are everywhere in our daily life and play a fundamental role in most of our activities. Looking towards 2050, the European chemical industry has the potential to be the building-block to the transition to carbon neutrality as an innovative industry contributing to new and currently unknown solutions to fulfil human needs. Although it uses fossil and renewable resources both as feedstock to make products and as a source of energy to generate heat, steam and electricity, at the same time, the European chemical industry is a vital solution provider to create a more energy efficient and low carbon economy e.g. lightweight materials in cars to save fuels and insulation materials to save energy for heating buildings. So, chemical industry is acting as a solution provider to other sectors of the economy, for all of the sustainable development challenges such as energy and climate, transport, health, food, hygiene, housing, among others.

However, chemicals apart from their contribution to the everyday living and the decarbonization of our planet, at the same time have hazardous properties which can cause harm to human health and the environment. To this direction the new chemicals and materials must be safe and at the same time sustainable. Based on this, EU has a comprehensive framework comprising approximately 40 legislative instruments including the Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the Regulation on the Classification, Labelling and Packaging of hazardous substances (CLP) and amongst many others the legislation addressing the safety of toys, cosmetics, biocides, plant protection products, food, carcinogens in the workplace as well as legislation on environmental protection.

World’s chemical turnover was 3,347 billion euro in 2018 and Europe was the second biggest producer (accounting for 16.9% of sales). The biggest producer, China is becoming a “great power” and is prevailing in international markets. On the contrary, EU share has halved over the last 20 years and forecasts predict a further decline by 2030 to move from second to third position, which is occupied from NAFTA. In 20 years, dropping from 32.9% to 16.9% is a remarkable number which can be justified apart from the increased competition from other regions, by comparably high energy prices, lagging innovation, currency appreciation, high labor costs, and regulatory and tax burdens.





: Cefic Chemdata International 2019

Unless specified, chemical industry excludes pharmaceuticals
Unless specified, EU refers to EU28

Regarding the EU industrial scape, the chemical manufacturing is the fourth largest industry in the EU, accounting for 7.6% of EU manufacturing turnover, comprising behind automotive, food products and machinery & equipment. It consists of 30,000 companies, 95% of which are small and medium size enterprises, directly employing approximately 1.2 million people and 3.6 million indirectly. EU turnover was €565 billion, where Germany and France are the two largest chemicals producers in Europe, followed by Italy and the Netherlands. These four countries accounted for 63.3% of EU chemical sales in 2018, valued at €357.7 billion. The share rises to 83.6%, or €472.1 billion, when including Spain, Belgium, and the United Kingdom. The remaining EU Member States accounted for 16.4% of EU chemical sales in 2018, to which Poland and Austria are the two largest contributors [1].

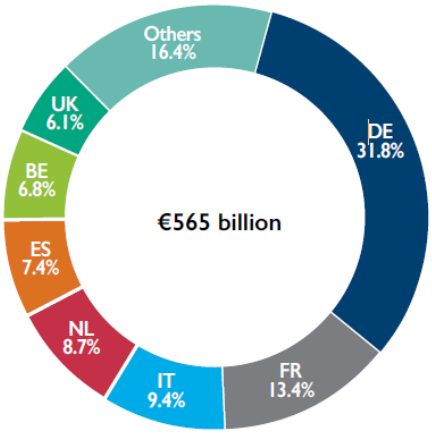


Figure 1 - Chemical sales by country: top 10. Source: Cefic[1]

The interests of the European chemical industry are voiced by Cefic (https://cefic.org/) which is the representative organisation of the chemical industry in Europe. Currently is representing 650 members and affiliates.

2.2 Types and Applications of Chemicals

The products of the EU chemical sector can be categorized into three main categories:

- Base chemicals: also known as commodity chemicals, represented 60.4% of total EU chemical sales in 2018 and cover petrochemicals and their derivatives (polymers) along with basic inorganics. The petrochemicals sub-sector covers manufacturing of chemicals using basic processes, such as thermal cracking and distillation. Polymers, in primary forms are, in most cases, integrated into petrochemicals sites. They also embrace the manufacture of resins, plastic materials and elastomers. The inorganic basic chemicals sub-sector includes production of chemical elements, inorganic acids such as sulphur acid, bases such as caustic soda, alkalis and other inorganic compounds such as chlorine. Finally, Base chemicals are produced in large volumes and sold in the chemical industry itself or to other industries.
- Specialty chemicals cover areas such as paints and inks, crop protection, dyes and pigments, and auxiliaries for industry (other chemicals such as glues, essential oils and gelatin). Specialty chemicals are produced in small volumes, but they nevertheless represented 27.2% of total EU chemical sales in 2018, an amount which is expected to continue to grow in the future.
- Consumer chemicals are sold to final consumers, such as soaps and detergents as well as perfumes and cosmetics. They represented 12.4% of total EU chemical sales in 2018.

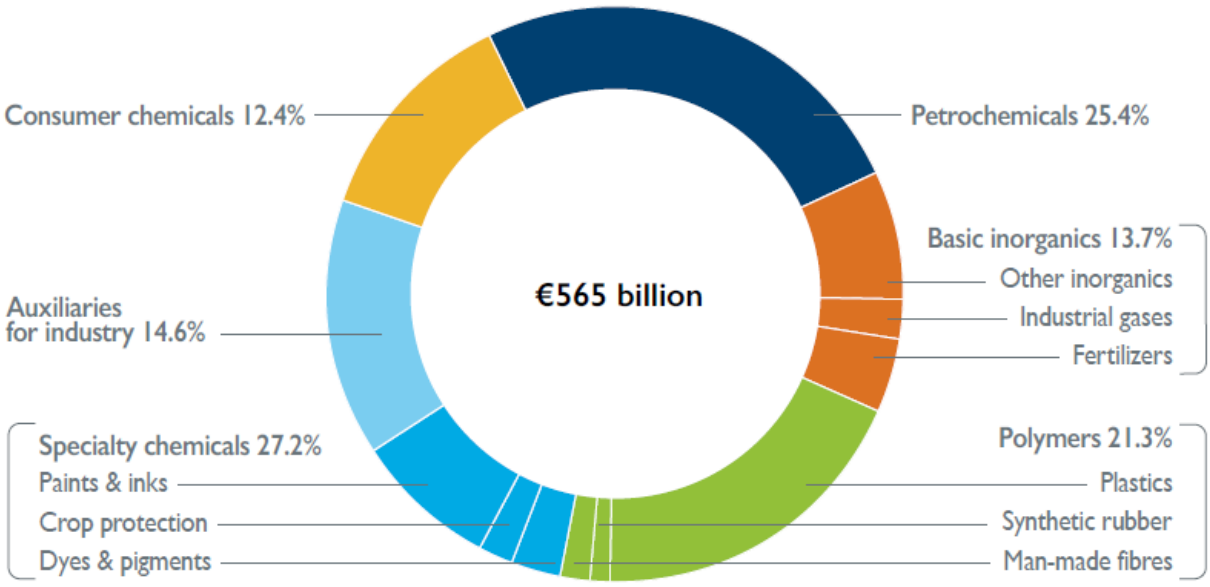


Figure 2 - EU chemical sales 2018 [1]

The International Council of Chemical Associations (ICCA) estimates that over 95% of all manufactured goods rely on some form of industrial chemical process. The industry produces a huge range of finished products for general consumption, including fertilizers, pesticides, and other agrochemical products that play a crucial role in feeding a growing global population, LED lighting which results in substantial power savings and roof and window coatings, used to improve insulation levels as part of climate change mitigation efforts. However the industry also produces key inputs, and enables processes, for other manufacturing activities that benefit living standards and consumers around the world. These include water chemistry, enabling the treatment, delivery, and conservation of clean drinking water that is critical to a number of SDGs, plastics used for packaging, which play a major role in protecting fresh, processed and prepared food, extending its shelf life and man-made fibres, such as nylon and polyester.

As mentioned before most of the EU chemicals are sold to downstream users, which are other industrial sectors [2]. Some of these industrial customers are the rubber & plastics industry, textiles industry, construction, computer production industry and pulp & paper sector. It is therefore evident that chemicals have a wide range of applications that further facilitate the transition to carbon neutrality and support sustainability.

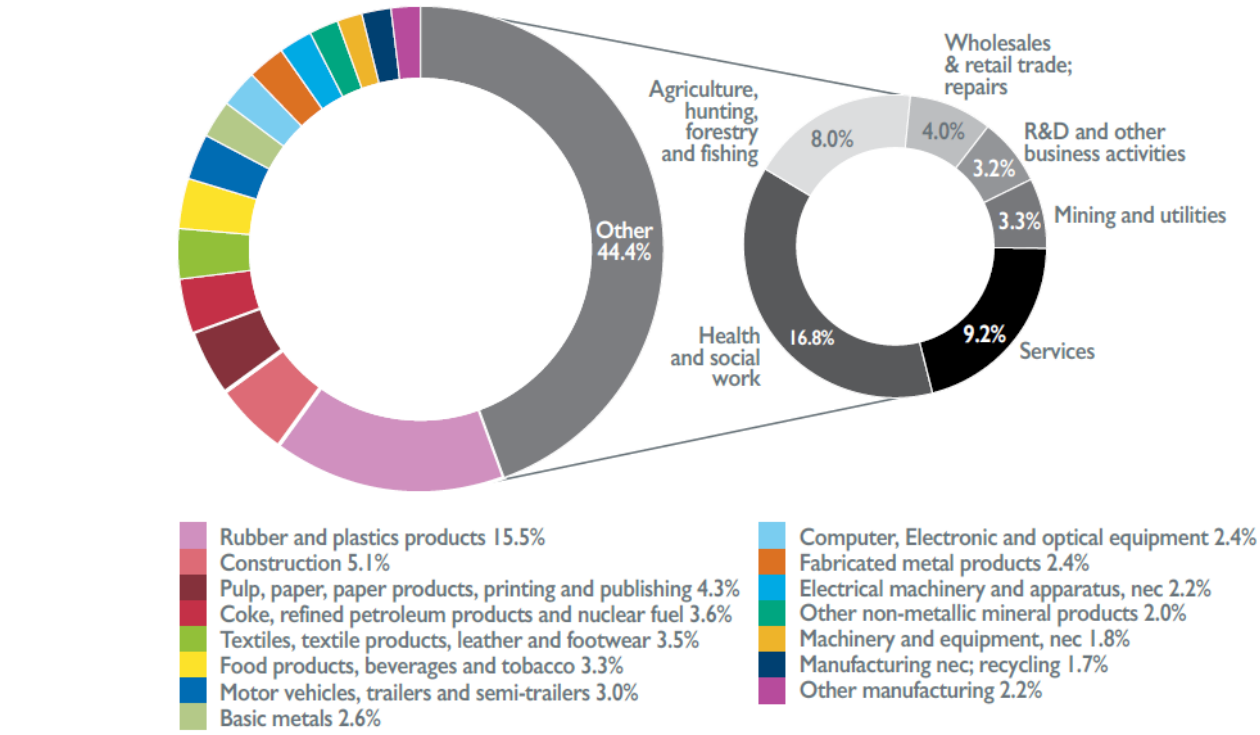


Figure 3 - Industrial customers of EU chemical industry [1]

2.3 Energy and GHG emissions

The chemicals sector covers a wide range of diverse processes, ranging from complex continuous processes making large-volume basic chemicals to smaller scale batch processes producing specialty chemicals and pharmaceutical ingredients.

Energy use in the sector is characterized by the use of natural gas to generate steam or for direct heating, and the use of electricity for a range of activities such as for pumping, compression, chilling, and lighting. The combustion of fossil fuel, indirect emissions from electricity consumption, and process emissions (resulting from processes that create CO_2 as a by-product of chemical reactions) make up the chemicals sector carbon footprint.

In 2017, the fuel and power consumption of the EU chemical industry, including pharmaceuticals, amounted to 52.7 million tons of oil equivalent and gas with electricity account for nearly two thirds of total energy consumption while energy consumption in chemicals accounted for 20.2% of total industry energy consumption in 2017[1].

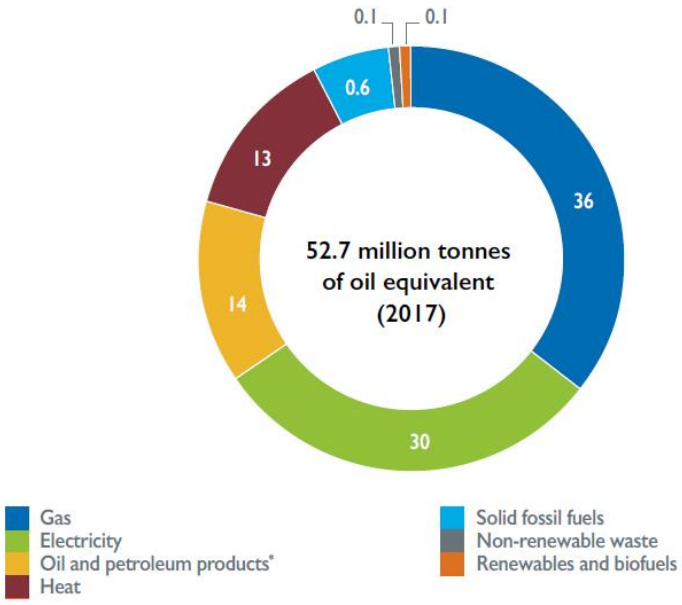


Figure 4 - Total energy consumption in the EU chemical industry by source* [1]

Many efforts have already been made to improve energy efficiency by reducing its fuel and power energy consumption per unit of production. To this direction there are significant differences over the years and these changes has led to a reduction of 24% compared to 1990 and simultaneously the share of renewable and biofuels energy consumption in chemicals increased from 0.3% in 2000 to 0.6% in 2017.

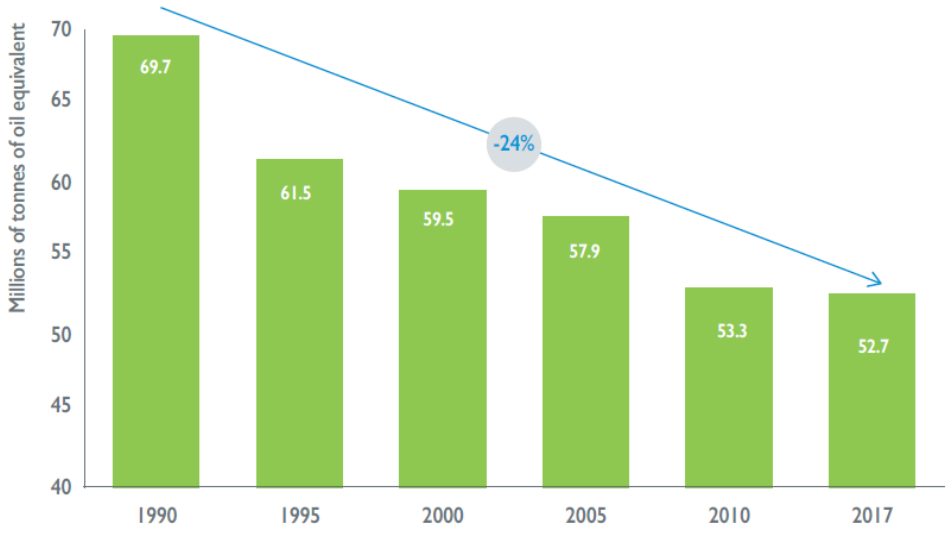


Figure 5 - Fuel and power consumption in the EU chemical industry* [1]

Regarding the gas energy consumption which is the sum of natural gas and manufactured gas the reduction reached the 30%. However still remains more than one third of total energy consumption which accounts for more than 21% of total industry consumption, and as far as concerns electricity consumption the chemical industry succeed to reduce the consumption by 13% since 1990. However the bigger reduction since 1990 was in the petroleum and solid fossil fuels where the reduction was 31% and 58% respectively.

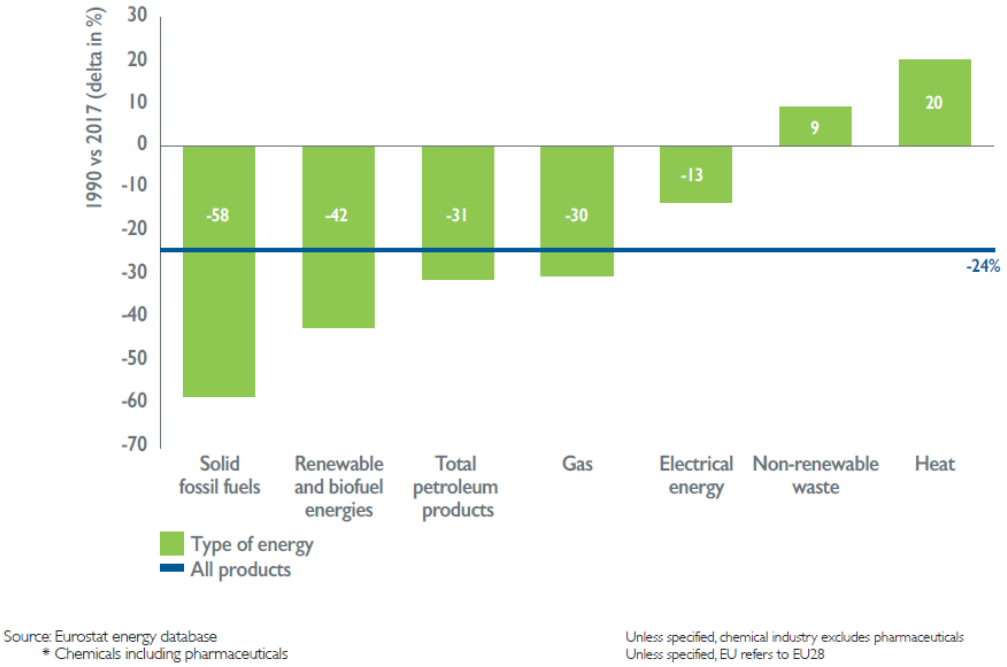


Figure 6 -EU chemicals energy consumption: 2017 compared to 1990 (delta in %)*[1]

Therefore, in absolute terms, the EU chemical industry has significantly reduced the energy composition from 1990 to 2017. Nearly half of this decline was driven by the reduction in gas consumption as a source of energy used. The most impressive reduction was the reduction of solid fossil fuels. All this facts has led to a 55% reduction in energy intensity compared to 1991 and characterizing EU chemical sector a pioneer in energy efficiency.

Regarding the **GHG emissions**, the sector is responsible for greenhouse gas emissions either directly through emissions from chemical process plants, or indirectly through the use of electricity generated by others. Direct emissions can be further divided into combustion emissions (e.g. related to burning fuel in boilers) or process emissions (where a greenhouse gas is produced as a by-product of the chemical reaction).

The chemical sector is the largest industrial consumer of both oil and gas, as well as the largest industrial energy consumer overall. However, it is the third industry subsector in terms of direct CO_2 emissions, behind cement and iron and steel. This is largely because around half of the chemical subsector's energy input is consumed as feedstock – fuel used as raw material input rather than as a source of energy [3].

Continuous efforts in terms of energy efficiency measures have already resulted in a decrease of total greenhouse gas emissions by 58% in 2017 compared to the 1990 level, despite an expanded production of 78%, showing a decoupling of production vs. emissions. However, this decoupling has limitations, and the major part of efficiency gains has already been leveraged, at least for the large scale chemical products.

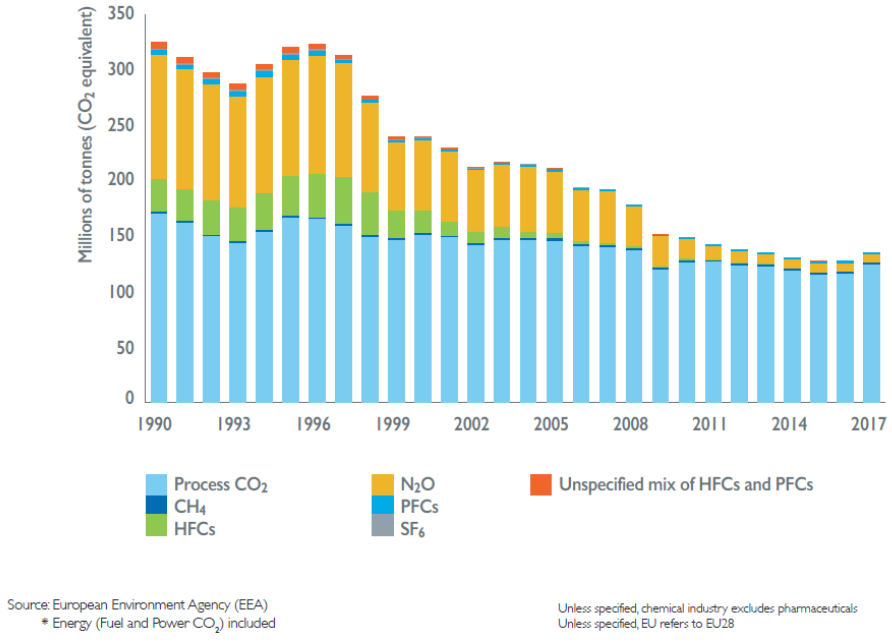


Figure 7 - GHG emissions in the EU chemical sector, millions of tons (CO_2 equivalent)*

According to the European Environmental Agency (EEA), the EU chemical industry, including pharmaceuticals, emitted a total of 135.2 million tons CO_2 equivalent in 2017. The most important pollutant which is CO_2 was partially restricted however, much of the decline is linked to abatement of nitrous oxide (N_2O) which is the second most important pollutant.

2.4 Production Processes

The energy-intensive nature of many chemical processes is justified by the high temperatures required for the processes. A range of technologies are used to deliver heat to chemical processes. The most widespread is the use of steam at a variety of different pressures. Steam is generated in boilers which are fired by natural gas or other fuels, or by heat recovery techniques. These techniques include heat removal from exothermic processes (those that generate heat as a by-product), heat recovery from waste streams, or heat exchange where a feedstock stream is pre-heated by cooling a product stream. Furnaces are also used to provide heat directly in some processes where very high temperatures are required, for example in the cracking stage of olefin production. Furnaces provide direct radiant heat compared to conduction of heat through a vessel or tube wall where steam heating is used. Natural gas or recovered waste gases are typically used as furnace fuels, although other fuels can also be used. Where the relative demand for heat and electricity is appropriate, many chemical plants improve their overall energy efficiency by using combined heat and power (CHP). CHP units may be physically integrated with the site, or located on a neighboring site. This is typically done using a natural gas fuel in a gas turbine to generate electricity, followed by a heat recovery steam generator. Alternatively, a steam boiler is used to raise steam to both provide heat and generate electricity via a steam turbine. CHPs often also make use of fuel or waste heat provided by the chemical process [4].

The most important chemicals that are considered as building blocks of chemical industry are:

- Methanol
- Ethylene
- Chlorine
- Ammonia (described in the fertilizers chapter)

Their importance is based on their large production volumes but also their energy and carbon intensity. A combination that is responsible for the most of CO_2 emissions of the sector.

Methanol

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 and to a very small extent also from heavy oil. Production volume was at 1.5 million tons in 2015.



Up to date methanol is almost exclusively produced in large scale plants up to 3000 tons per day capacity from synthesis gas, which again is generated by reforming of natural gas. Carbon monoxide and hydrogen react over a catalyst to produce methanol. One can produce methanol from CO as well as from CO_2, whereas in the production from CO_2, a water-gas shift step needs to be included to remove excess CO_2 from the feed-gas stream. Emissions are at 0.52 tons per ton of methanol for natural gas [5].

CO Hydrogenation: $CO + 2\ H_2 \rightarrow CH_3OH$

CO_2 Hydrogenation: $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

The general process scheme can be described in a simplified manner as follows: after feed purification, mainly desulphurization, the feed is pre-heated and steam is added to the natural gas. The mixture is fed into the reformer at 20 bar pressure, in which hydrogen and carbon monoxide (syngas) and around 5% CO_2 (with also some remaining residue methane) are formed in the catalytic steam reforming reaction at 800-950°C. The process gas is cooled in a process boiler, producing steam for the process and excess steam, which can be exported. A high level of heat integration is ensured. Some CO_2 is added to the feed gas to adjust the syngas to have the ideal ratio to efficiently produce methanol.

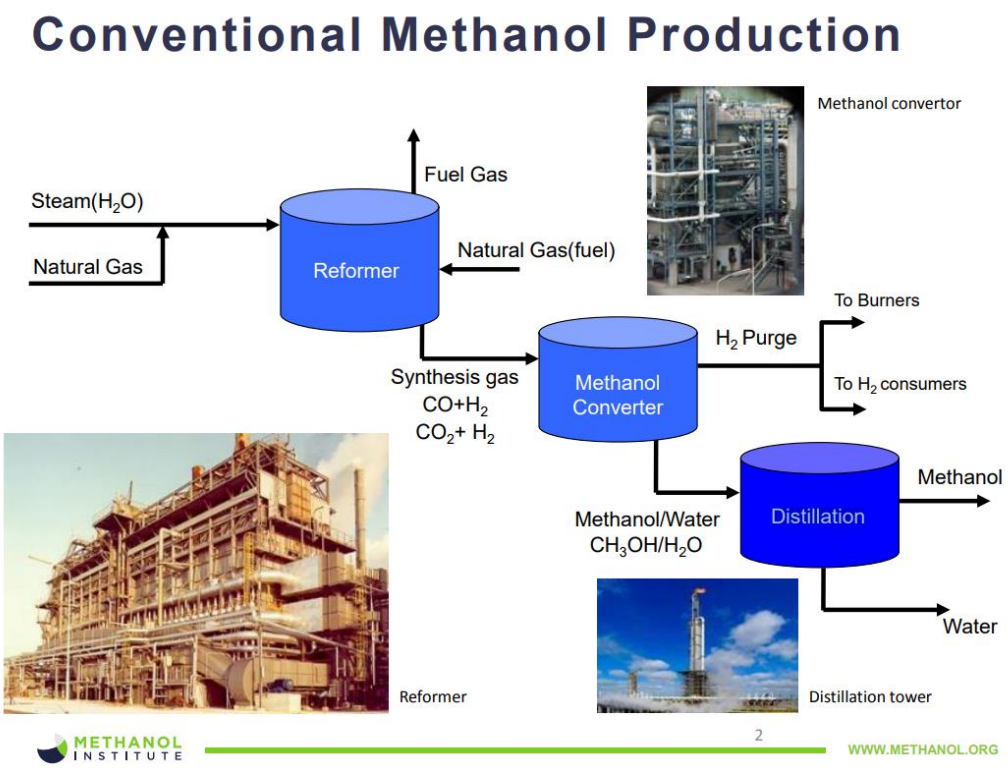


Figure 8 - Methanol production. Source:www.methanol.org

For the subsequent methanol synthesis, a large variety of reactor designs is available from different licensors, the technology is therefore described in general terms. The syngas is compressed and fed into the methanol converter. Methanol conversion is at approximately 5% per pass, hence unreacted gases are recycled in the synthesis loop. The converter design affects the loop pressure. The synthesis loop comprises a circulator and converter. Reaction heat from the loop is recovered as steam. A purge from the synthesis loop is taken to continuously remove inert gases accumulated during the recycle loops and sent to the reformer section. The crude product contains water and traces of byproducts. Non reacted gases are removed in a separator and methanol is separated from water by distillation. The specific energy consumption of the methanol process in Europe is at 12.5 GJ/t methanol, which mainly comprises fuel in the reformer, with 0.6 GJ/t of electricity use. Best practice technology level is around 9.8 GJ/t [5]. Sufficient heat is produced in the process to run the methanol distillation, in fact, methanol production is a net steam exporter of around 2 GJ/t methanol.

Ethylene

Production of ethylene in Europe is mainly performed by steam cracking with Naphtha as the predominate feedstock, although Liquefied Petroleum Gas (LPG) is gaining importance, and 25% of feedstock used in the steam crackers in 2015 was LPG [6]. Usually crackers can use a mix of feedstock, and very few crackers would use LPG only. Also Ethane could be used as feedstock.

The process starts with mixing the feedstock with steam and heating in furnaces to 750 - 900 °C, where naphtha is cracked into products of lower chain length. The cracked gas is subsequently cooled down, thereby recovering the heat as steam. Benzene, toluene, xylene are separated at around 150°C, water is removed and the remaining gas is compressed, followed by fractionation of the gas into the different products. Methane is recycled as fuel into the furnace. A higher cracking severity favors ethylene production whereas lower severity yields higher amounts of propylene. The specific energy consumption of Naphtha-based steam cracking in Europe is around 16.5 GJ/t, the value for best practice technology plants is around 12 GJ/t[5].

Chlorine

Chlorine and caustic soda (co-product) are basic building blocks for thousands of useful substances and products. About two thirds of European chlorine production is used in engineering materials, polymers, resins and elastomers. The largest single end use (35%) is PVC plastic for the construction, automotive, electronics and electrical industries.

There are three main production technologies to produce chlorine[7]:

• Membrane cell process, most widely used in Europe (85% of installed capacity)



• Mercury cell process, now phased out in Europe

• Diaphragm process for about 10% of installed Europeancapacity

The membrane technology and non-asbestos diaphragm technology are considered best available technologies (BAT).

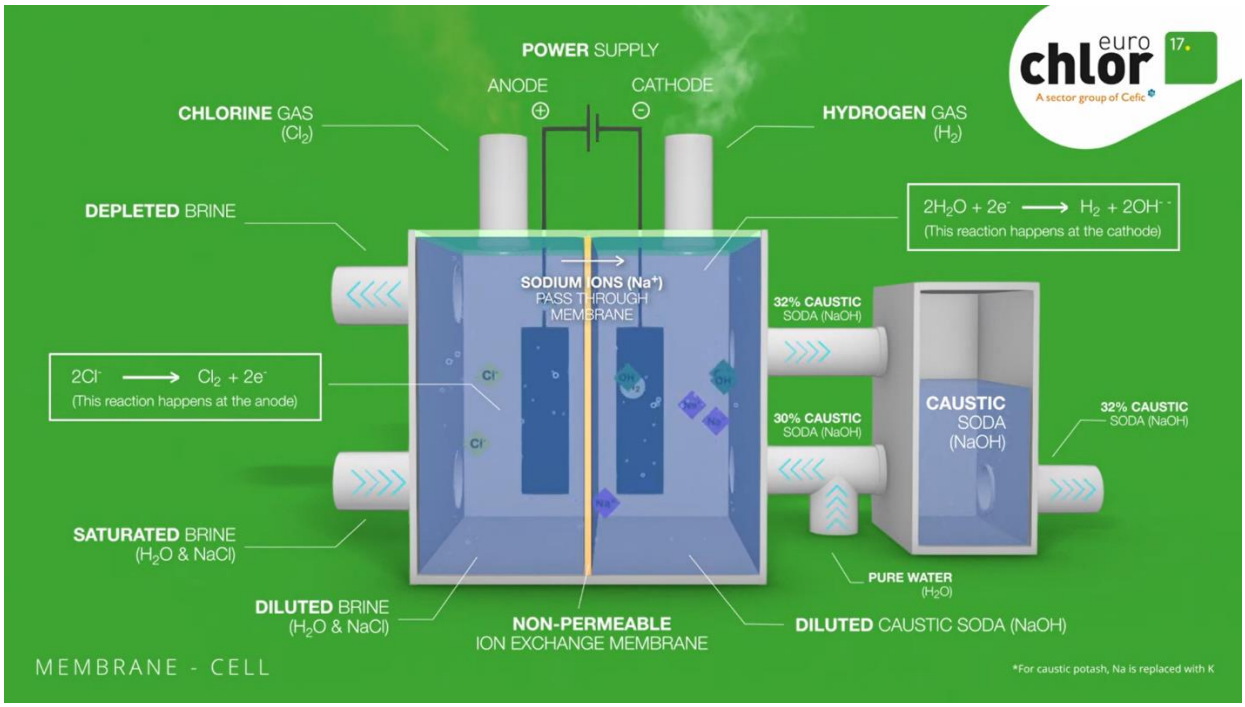


Figure 9 - Membrane Technology. Source:www.eurochlor.org

By the nature of the chemical reaction, chlorine, caustic soda and hydrogen are always manufactured in a fixed ratio: 1.1 tons of caustic and 0.03 tons of hydrogen per tons of chlorine. This product combination is called an Electrochemical Unit or ECU. The average electricity consumption of a chlorine electrolysis plant is about 3.3 MWh per ECU in 2010. About 90% of the electric current is used as raw material which cannot be substituted. The reduction potential of the consumption is therefore limited and is mainly due to technology shift from mercury cell to membrane technology together with smaller efficiency measures in the production units. About 10% of the electricity is used for lighting and operating pumps, compressors and other necessary equipment. Also steam is needed in the chlor-alkali production e.g. for salt preparation and concentration of the caustic soda, the amount of which is less than one ton per ton of caustic soda.

The technology shift from mercury cells to membrane will lead to a lower electricity consumption in the sector. A membrane plant uses less electricity than a mercury plant, but requires more steam.

The average electricity consumption per ton of chlorine produced equals a CO_2 emission of about 2.1 tons. However, the chlor-alkali industry does not emit CO_2, instead the emissions occur during the production of the electricity that the sector uses i.e. the chlor-alkali industry is an indirect emitter of $_{CO2}$.

2.5 Decarbonization potentials

The chemical industry has a crucial role in Europe's transformation to a more energy efficient and low carbon future. To these direction the sector has already made significant steps and has reduced its GHG emissions. However further decarbonization potentials need to be studied and implemented in order to succeed the carbon neutrality.

Deep emissions reduction in Europe is technically possible through power supply decarbonisation and CCS integration with chemical processes in the 2030–2050 timeframe [8]. A range of current and future technologies can sustain Europe's track record of energy and emissions intensity improvements: final energy demand can be maintained at a constant level, and emissions could be virtually eliminated with energy efficiency (33% of the total emissions reductions), CO_2 capture and storage (CCS) (25%), renewable electricity (20%) and fuel switching and measures to reduce nitrous oxide emissions (22%). To enable continuous and competitive production, access to large amounts of affordable and reliable energy and feedstock will be necessary, which can be challenging for renewables [9]. Infrastructure will be crucial, including transmission grids for renewable power, pipelines for hydrogen, $_{CO2}$ and heat, and waste logistics and recycling.

According to the International Energy Agency's (IEA) Reference Technology Scenario (RTS), global sectorial CO_2 emissions would grow by around 40% globally from the current level, in line with a plastics demand growth of 600 Mt/yr [10].The Clean Technology Scenario (CTS) estimates direct annual CO_2 emissions of 0.8 Gt by 2050, equivalent to a 60% reduction compared to the RTS. The IEA's analysis focuses on the reduction of emissions from direct energy use and processes that only cover two-thirds of the sector's total life cycle emissions. Energy efficiency therefore plays a key role in the IEA's analysis, contributing 25% to the mitigation effort. The role of alternative feedstock and plastics recycling is limited to 15%. The IEA analysis suggests a continued importance of fossil fuel use in the sector, which is inconsistent with net zero by 2050.

According to Ref.[11] electrification of processes and new catalytic conversion routes can be listed as key options. Biomass and recycling are key strategies to reduce fossil feedstock use, while CO_2-based fuels and chemicals are unlikely to be significant contributors to global abatement in the next two decades. For energy supply, clean hydrogen, heat pumps and waste energy use, as well as energy management systems, are low-carbon options for decarbonisation.



Regarding the most important chemicals some potential solution that have high TRL are the followings.

Methanol

The alternative low-carbon pathway to methanol is again based on hydrogen, produced by water electrolysis with low-carbon electricity followed by hydrogenation of CO_2 as carbon source.

Electrolysis: 6 H_2O + electrical energy (wind/solar) →6 H_2 (cathode) + 3 O_2 (anode)

Hydrogenation: 2 CO_2 + 6 H_2 ↔ 2 CH_3OH + 2 H_2O

Total: 2 CO_2 + 6 H2 + electrical energy (wind/solar) →2 CH_3OH + 2 H_2O + 3 O_2

Hydrogenation of CO_2 is used also in conventional methanol production by adding small amounts of CO_2 to adjust the CO/H_2 ratio of the syngas. Synthesis of methanol from CO and CO_2 are tied through the water gas shift reaction.

Water gas shift: CO + H2O → CO_2 + H2

Ethylene

The production pathway of low-carbon ethylene is based on the previously described methanol production from hydrogen and CO_2 followed by the methanol to olefin process (MTO), which is currently commercially deployed, although commercial operations are located in China and no MTO plant is operated in Europe so far.

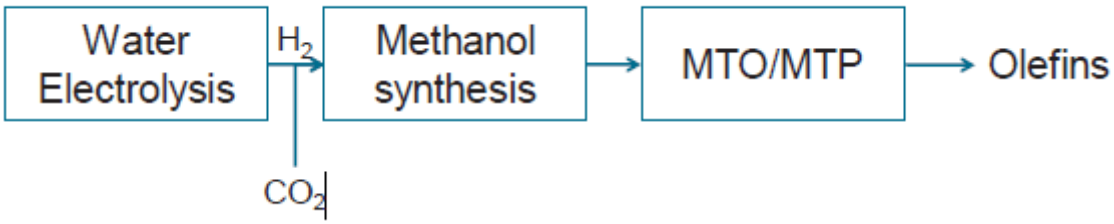


Figure 10 - Low-carbon process sequence to ethylene and propylene via low carbon methanol [12]

Reactions:

2 CH3OH→CH3OCH3 + H2O

CH3OCH3 → C2H4 + H2O

Depending on the catalyst, different target products can be realized subsequently, besides MTO the methanol-to propylene (MTP) process, or methanol to gasoline (MTG) process shall be mentioned.

Chlorine

For existing chlorine plants, three measures have been taken into account. Conversion of mercury cell plants to membrane cell technology, changing monopolar to bipolar membrane technology, and the retrofitting of membrane cell plants operating in 2010 to oxygen-depolarised cathodes technology

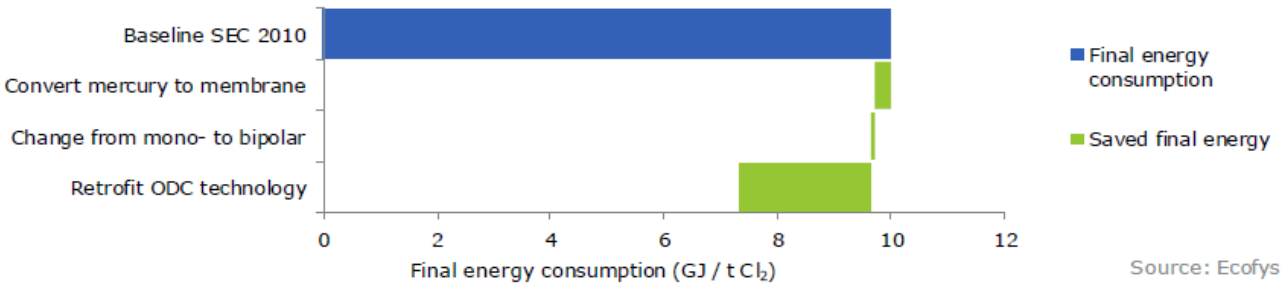


Figure 11 - Technical potential for energy efficiency improvements in existing chlorine plants in 2050 [13]

For new plants, membrane cell technology is the best available technology and considered the baseline technology for future chlorine production. The power consumption of new electrolyser cells shows limited improvement thought. An alternative technology, also using brine as feedstock, is oxygen-depolarised cathodes (ODC), giving reductions of up to 30% of electricity compared to new conventional membrane plants (see ODC above).

Improvements in feedstock

The chemical industry uses both fossil fuels and biomass as feedstock. For Petrochemicals, the feedstock is mainly oil derived (e.g. naphtha used in the steam cracking process), and for Basic Inorganics, natural gas is used for the production of ammonia. The use as feedstock forms a significant part of the use of fossil fuels and biomass in the chemical industry

These GHG emissions can be reduced by efficient utilization of existing feedstock and the use of alternative feedstock. Three options can be distinguished:

- The use of renewable resources such as biomass
- Recycling, i.e. the use of secondary feedstock like industrial and post-consumer waste streams
- The use of other alternative feedstock such as the capture and utilization of CO_2.

Feedstock for bio-based chemicals

Bio-based chemicals can be produced from many types of bio-based feedstock, e.g. starch, sugars, vegetable oils, animal fats or lignocellulosic19 material. Biomass feedstock is typically divided into three generations. Within the area of biofuels, there is no widely agreed definition of first, second and third generation biofuels. No single, agreed definition exists. In general, the following distinctions

can be made [13]:

- First generation bio-based products are made from simple molecules, using existing technologies such as fermentation or transesterification. Sugars and vegetable oils found in arable crops are used as feedstock in these processes. First generation feedstock is already commercially converted into chemicals
- Second generation is typically used to describe bio-based products made from (ligno-) cellulosic biomass, such as woody crops or agricultural residues like straw. Typically fermentation is used, but the lignocellulosic material first has to be broken down to simple sugars, which is a more complex process.
- Third generation biomass is used to describe more advanced options that are further from commercialization, such as algae.

Valorization of waste: Recycling of plastics

Valorization of plastic waste streams, residue streams and recovery of end-of-life products takes place around Europe. What is today considered as an industrial waste or post-consumer waste could entirely or mostly be used as feedstock, e.g. part of the raw material mix, by other industrial sectors in 2050.

Three options for recycling of polymers are distinguished in this Roadmap:

1. Back to polymer (=mechanical recycling): Collection and mechanically processing of waste plastics to produce recycled polymers.

2. Back to monomer (=feedstock recycling): Breaking down certain polymers into their monomers by means of a chemical process.

3. Back to feedstock (=feedstock recycling): Breaking down polymers into hydrocarbons or a mixture of carbon monoxide and hydrogen by means of a thermal process.

Utilization of captured carbon as feedstock

Carbon capture and utilization (CCU) comprises a broad range of processes involving the use of CO_2 in the fabrication or synthesis of products and the energy required must be produced “carbon-free” to avoid further production of CO_2 to generate the energy required.

For almost all applications in the chemical industry, the CO_2 needs to be available in pure or highly concentrated form, meaning that after capturing the CO_2 needs further treatment and purification. The utilization of CO_2 (CCU) could be developed in symbiosis with carbon capture and storage (CCS). If investments in pipeline infrastructure required for CCS are made, these could also serve



as a feed-infrastructure for CCU applications, while the storage functionality delivered by CCS could ensure optimal use of the CCU-based plants. On the other hand, CCU could potentially accelerate improvements in capturing technologies, increase public acceptance for CCS and be an alternative for CCS in places where storage of CO_2 is not possible.

Regarding the utilization, there could be utilization options that assure a permanent removal, e.g. with the carbon ending up locked in minerals. For other options the utilization is only temporary, and varies from days to tens of years, like in urea or polymers. When assessing the effect of utilization of captured carbon, this should be taken into account and the overall GHG emission performance should be accounted for.

Improvements in energy efficiency of processes

Since 1990, the European chemical industry has put tremendous effort into the improvement of energy efficiency, however in order to achieve the environmental goals, higher energy efficiency of the processes is essential.

Efficiency gains, thought improvements, are a mix of continuous retrofits of existing plants to reduce the specific energy consumption (usually incremental improvements) and replacement of old plants/building of new plants thereby using the available technologies that represent the best performing plants.

Further measures to reduce the carbon-intensity of the currently used processes via efficiency measures may include [12]

- Incremental improvements,
- Implementation of best practice technologies, i.e. production with plants at the highest available energy efficiency level
- advanced heat integration
- further advancements such as the use if process intensifying equipment

Use of renewables & CHP

Another important measure that can be helpful to the reduction of the GHG emissions is to increase the use of renewable energy. Geothermal power can provide heat to some chemical processes. The low prices show that geothermal heat could become, in some cases, an attractive source of low temperature heat in the future, however, the potential is limited due to the geographical availability and that temperature limits(up to approximately 250 °C) [13]. Another option to these direction is the use of combined generation of heat and power (CHP) which can save fuel compared to generating



heat and power separately if the heat can be used. However for further decarbonization CHP should be used in biomass applications and / or in combination with carbon capture and storage.

Carbon capture and storage (CCS)

Although carbon capture is not a new technology, capturing CO_2 with the intention to combat climate change is relatively new, and up to now, only occasionally applied.

In most cases, the captured CO_2 needs to be transported to the place where it is either stored or used. Large amounts of CO_2 are most efficiently transported either by pipelines or by ship. Before transportation, the CO2 needs to be purified and compressed / liquefied. The costs for transportation of CO2 depend on transport volumes, transport distance and possibilities to use existing infrastructure.

In general, the investment cost of CCS is high and the attractiveness depends on CO2 emissions volume, so, the larger the volumes of captured CO2, the cheaper all the steps of CCS. The step of CCS are mainly the capture and compression, the transport and the storage. Finally by building new installations and acquiring technical knowledge the cost will eventually go down making this technology more widespread.

Apart from CCS, the captured CO_2 can also be used (CCU) as feedstock, as mentioned before, as raw material for inorganic materials, but also to enhance hydrocarbon production (enhanced oil recovery, enhanced coal bed methane), in the food industry (soft drinks), in greenhouses for enhancing growth of the plants and in the production of fuels.[13]

To sum up, the road to the decarbonization of EU chemical industry is a really complex that can be solved and the solutions vary depending on the chemical sector, however the big steps and the large savings of CO_2 emission will come from the fertilizers that simultaneously are produced in large volumes and their production is carbon intensive. To this direction there are some large potentials that can be considered as game players. The first one is the use of hydrogen in the production of ammonia and methanol and the second is the use of biomass as feedstock. Regarding the use of hydrogen the generation of hydrogen is considered as one of the most energy-consuming processes so the possibility of using hydrogen from renewable energy sources could significantly reduce the fossil-fuel use and GHG footprint of these processes. So, although electrolytic water cleavage, which is a highly energy-intensive process and requires more energy is interesting from a GHG-saving perspective. However from an economic perspective, the costs for hydrogen from electrolysis are currently roughly twice of those from gas steam reforming, so significant improvements to the energy efficiency and cost of these technologies are needed to make them economically viable. As far as concerns the use of biomass also is a game changer since has some important benefits. The first



one is that the use of biomass will reduce the dependency on fossil fuels which are the source of most GHG emissions in chemical processing. Also that biomass material absorb CO_2 while growing, which can be used to counterbalance against emissions produced during manufacture or even during destruction or waste, and finally biomass sources are renewable, while fossil fuels are finite and likely to show larger price volatility in the future.

2.6 Challenges and policy recommendations

As an energy intensive industry, chemicals are dependent on climate change and energy policies, therefore, EU chemicals industry is under severe competitive pressure. It faces challenges that include increased international competition, rising energy and feedstock prices, pressure to increase resource efficiency, new regulations, and the need for innovation.

These are some policy measure that needs to be taken into account in order to remain the EU chemical industry competitive and in the same time be a frontrunner in decarbonization of the planet.

Differences in energy and feedstock prices as well as energy and climate policy costs between Europe and the rest of the world determine whether growing demand for chemical products will be met by production in, or outside of Europe. Current energy and feedstock price differences with key competing regions outside Europe jeopardize the competitiveness of Europe's chemical industry and the value chain it supports. If such differences were to persist, and in addition, policy cost differences were to further increase, for example due to policy-related levies on electricity prices in the EU and unfavorable EU emissions trading system rules, this would result in a negative trend in the trade balance for basic chemicals and lead to significant carbon leakage. The implementation of the above-mentioned measures should be designed to complement the future carbon framework. The goal must be to produce GHG intensive products – taking the whole production value chain into account – as carbon efficiently as possible irrespective of the location. This future carbon framework should be designed to ensure this happens as cost effectively as possible. As the global framework is being developed, local policy should ensure that carbon burdens do not apply unilaterally within their regions thus avoiding market distortions and unintended consequences such as carbon leakage. Hence, the development of a **global carbon framework** to accelerate GHG reductions in order to avoid market distortions and minimize carbon leakage because the challenge of GHG emissions must be tackled globally as emissions are global. Global policies will help minimize carbon leakage and reduce the risk of market distortions. Such distortions would be created where higher costs are incurred by some, but not all major industries and/or regions through stricter regulations. In order to avoid such dangerous situations harmonized global policies are essential. Also local transitional provisions such as free carbon allowances may be needed.



Another important aspect that policy must support is the reduction of energy use thought extended **energy efficiency**. Energy production and use is one of the greatest sources of CO_2 emissions and needs to be a priority focus area in the drive towards a low-carbon future. To this direction Government policies should give more support to those products and applications that offer greater energy and resource efficiency, e.g., building insulation.

The choice of **feedstock** could also play a crucial role to the decarbonisation of the industrial sector. The chemical industry can use a wide range of products for both feedstock and energy, so it is important to support the development of the most efficient and sustainable use of available feedstock and energy. Taking these into account, governments should be careful with restrictions and legislations about feedstock because there is the potential of harming economy without really reducing the GHG emissions. Technology development will be required and the use of **bio-feedstock** is a promising option. In extension of this, the dispose of chemical product is unequal across regions and has a significant impact on the total emissions over the life cycle of a product so most **efficient and sustainable disposal, recovery and recycling options** are need. To succeed this implementation the policies should support the development of new technologies and practices.

As suggested above the support the development and implementation of **new technologies** is of high importance. The research and development of new technologies to meet this challenge will need funding and support. In a field of rapid technological progress, however, it is important to avoid locking in sub-optimal solutions and despite the current economic situation, governments should continue funding **research and development**.

Regarding research and development the Europe should support more programs that facilitate the transition and give the **lowest cost abatement opportunities.** Since the reduction of CO_2 emissions is urgent and funds are limited it is vital to spend wisely and focus on those measures that can have the greatest impact. Therefore, Policy should focus on scale, cost, and implementation speed.

It is essential that the energy and climate policy framework in the EU stimulates sustainable and efficient growth. Under these conditions, innovations and breakthrough technologies that can mitigate global emissions will deliver their full potential. A stable and predictable policy framework, dynamic enough to adapt to a changing global energy and climate policy outlook, will create increased certainty for business to undertake the path to a more energy efficient and low carbon future.

As far as concerns the motivation of industries that reduce their carbon footprint, some kind of **reward** should be given to **early movers**. Policy should ultimately reward those companies that are most advanced in implementing CO_2 reduction measures and simultaneously use effective



measures to accelerate action in those companies and regions that have fallen behind, always establishing practically achievable emission targets.

To unlock the potential of sustainable chemicals, the EU chemicals industry requires fair and non-discriminatory **access to biomass** at competitive prices, as well as favorable legal and regulatory framework conditions. Although the chemicals industry generates growth, the European share of global production is declining and investment in new capacity is low. To encourage investment, the industry requires access to critical inputs (in particular, energy and raw materials) at competitive prices that reflect international cost conditions.

Last but not least we need it important to see the big picture. The best options to reduce global GHG reductions will involve a **full life cycle approach** to ensure that each stage of the value chain will provide its optimum contribution.



3. Fertilizers

3.1 Historical background

Through centuries of ancient and medieval times, men have been really interested in improving crop yields by the addition of various mineral or organic substances. By the time of the early Roman and Grecian writers, there was much concern about what materials were the best fertilizers. Until the last 200-300 years, however, the approach to the subject was highly empirical, it was found by accident or by trial and error that applications of various organic wastes or mineral substances to the soil dramatically improved plant growth. Illustrations are manure, ground bones, wood ashes, saltpeter, and gypsum, with the manure to be throughout history the basic input of nutrients for plant production. However the results were not predictable, so a treatment that benefited one field might have no effect or even an adverse effect on another [14]

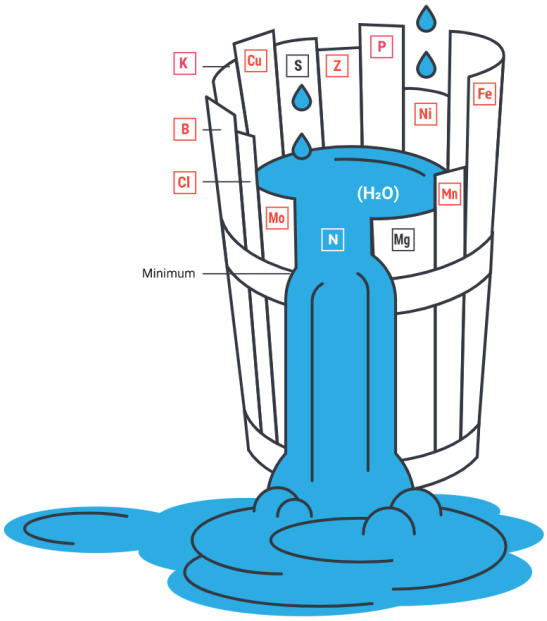
With the development of agricultural production and increasing food demand, farmers searched methods to improve efficiency on their fields. Animals were not necessarily held on every farm and manure was not available to fertilize soils. With increasing urbanization, the circulation of nutrients from animals and humans into the soil became more difficult. With the development of commercial fertilizers, this nutrient gap has been somewhat closed. The application of fertilizers increases the production of biomass in the plant and thus yields. Therefore, it contributes to address the major challenge of feeding a growing world population [15]

The foundation for the modern fertilizer industry was laid by Justus Liebig in 1840. He was concerned with what elements a plant needed, where it got them, and which farm practices helped the most. His influential works first denounced the vitalist theory of humus, arguing first the importance of ammonia, and later the importance of inorganic minerals.

Liebig propounded the "Law of the Minimum," which is still a useful concept despite its lack of quantitative exactness. The yield potential of a crop is like a barrel with staves of unequal length. The capacity of the barrel is limited by the length of the shortest stave and can only be increased by lengthening that stave. When the stave is lengthened, another one becomes the limiting factor [16]. So, this law states that, if one of the nutritive elements of the soil or air be deficient or lacking in availability, growth will be poor even when all other elements are abundant. If the deficient element is supplied, growth will be increased in proportion to the amount supplied up to the point where the supply of that element is no longer the limiting factor. Increasing the supply beyond this point is not helpful since some other element is now in minimum supply and becomes the limiting factor [14].



Figure 12 - LIEBIG'S LAW OF THE MINIMUM / Source: The Fertilizers Institute



At that time in England Sir John Bennet Lawes was experimenting with crops and manures at his farm at Harpenden in 1839 and in 1842 Lawes patented his process. He began producing superphosphate of lime on a commercial basis in 1843 and for more than 100 years, superphosphate was the dominant P fertilizer in the world.

Concurrent with the development of the P industry, a K industry also developed and Liebig was the first recommended ashes as the source of K in 1840. The K fertilizer industry started in Germany in 1861. Modern K fertilizers are more the product of physical than of chemical processes [17].

Regarding N industry, Lawes together with Sir Joseph Henry Gilbert, who had studied under Liebig at the University of Giessen, published research showing that the addition of N fertilizers increased wheat yields. Fifty years later and under the weight of the food crisis, many chemical researchers set out to find a solution to the production of N fertilizers. The solution was provided in 1909 by Nobel Prize-winning chemists Carl Bosch and Fritz Haber, who discovered that the chemical reaction of atmospheric N and hydrogen produces ammonia which is the main ingredient in nitrogen fertilizers today. In July of that year, Germany's largest chemical company, BASF, funded German chemist and engineer Carl Bosch to develop ammonia production on a commercial scale. Today, a modern ammonia production plant produces about 1,000 tons of ammonia per day. The N fertilizer industry, after the World War II became dominant [16].

Finally, urea, one of the first N synthetics fertilizers, was first synthesized commercially in 1920 using ammonium carbamate and today and it is by far the most used fertilizer, globally, expressed in terms of nutrient followed by nitrates [15].

3.2 European fertilizer industry

The United Nations' Food and Agriculture Organization (FAO) estimates that by 2050 the population of the world will have reached 9.1 billion people which leads to a demand of 60% above the levels of 2005/2007 [16]. Mineral fertilizers enables almost half of the global population to be fed so the fertilizer industry can be considered as one of the oldest and large scale chemical industries.

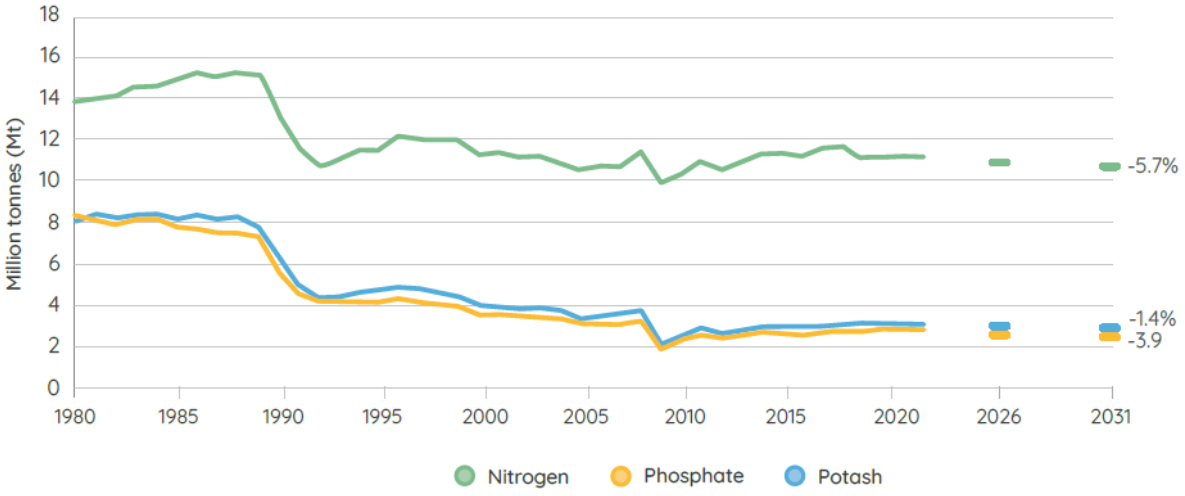
Each year, the European fertilizer industry transforms millions of tons of air, natural gas and mined ores into products based on the three essential plant nutrients nitrogen, phosphorus and potassium, ammonia being the building block of most fertilizers. The use of fertilizer at global level is increasing on an annual basis by around 2 % for phosphorus and potassium and the growth rate for nitrogen-based fertilizer is higher and in particular for urea which represents the 47% of the nitrogen fertilizer consumption[15], [18].

The interests of the European fertilizer industry are voiced by Fertilizers Europe (www.fertilizerseurope.com/). Currently, the association is representing 17 corporate members and 7 national organisations. It employs 74,000 people (including supply chain) and has a turnover of € 9.5 BN.

Figure 13 - Map of major fertilizer plants in Europe. Source: Fertilizers Europe 2018

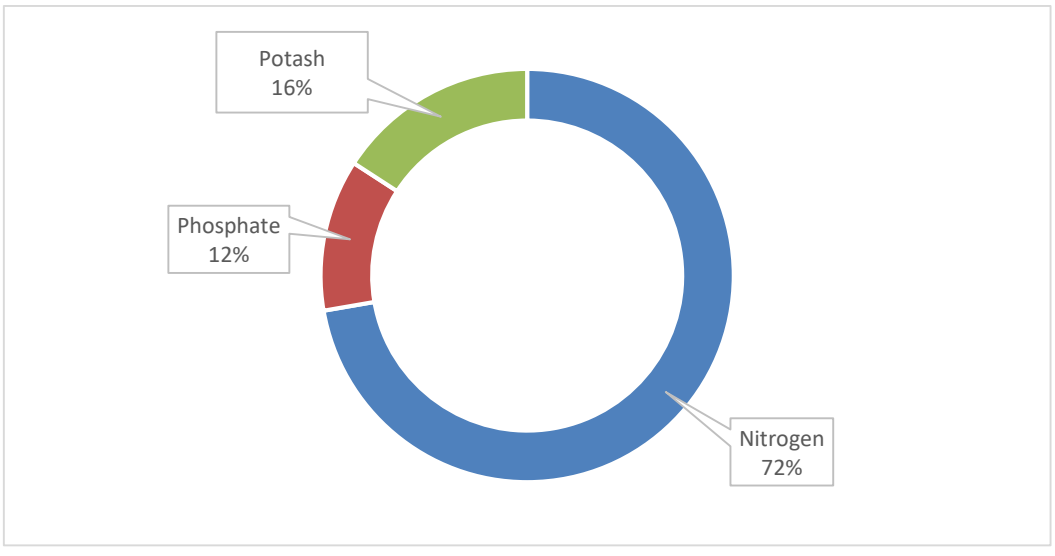


Figure 14 - EU Fertilizers consumption in the EU. Source: Forecast of food and farming and fertilizer use in the European



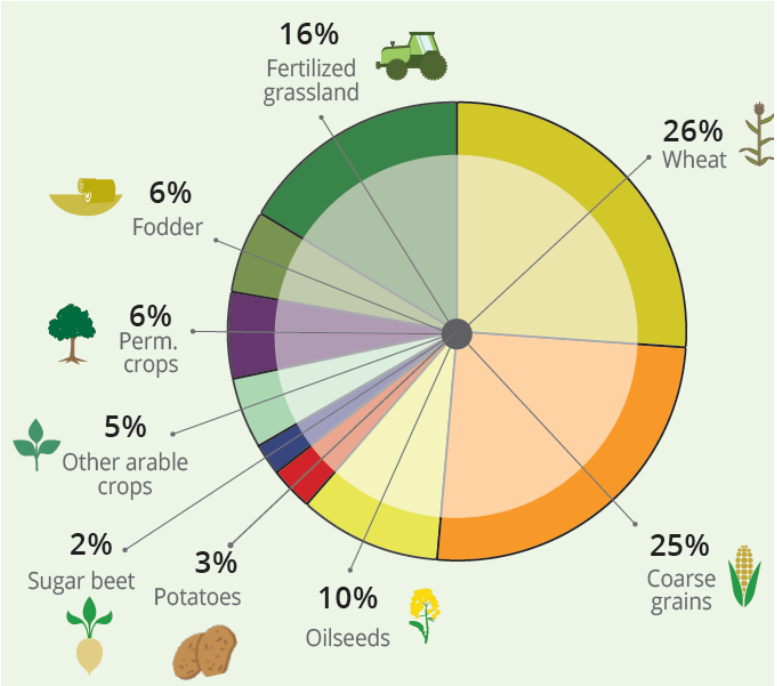
The European fertilizer industry has more than 120 production sites scattered throughout majority of European Countries. The EU production of fertilizers is relatively small with the total production to be reaching 16.8 Mt in 2019. From this amount the nitrogen represent the 73%, the phosphate the 12% and the potassium accordingly the 16%. On a global lever the total volume of fertilizers produced, measured as nutrient weight, was 254.1 Mt. Of the total volume, nitrogen represented 59%, phosphorous 25 % and potassium 16 %. When the production is measured as share of the global production, The EU production represents only the 8 % of the nitrogen, the 3 % of the phosphate and the 6 % of the potash is produced within the EU [19] .

Figure 15 - Europe Fertilizer Market, Share in %. Source: Fertilizers Europe 2019



France accounted for the largest share in the European fertilizer market. As per Eurostat, France held 19.6% of the total market share in 2019, followed by Germany and Poland. Worldwide China is the absolute dominant in fertilizers production followed by India. Regarding the imports of fertilizers as a share of EU consumption reaches the 30% of N, the 68% of P and the 85% K. The most imports to Europe are from Russia and in particular in 2020, 1120Mt of fertilizers where imported [19].

Figure 16 - Fertilizer consumption by crop in the EU. Source: Fertilizers Europe



Around half of the fertilizers used are applied on cereals (26% on wheat, 25% on coarse grains), 16% on grassland and 10% on oilseeds. The total volume of fertilizers applied on specialised crops (potatoes, sugar beet, and permanent crops) is relatively low – 11%. The application rate per hectare varies considerably between different crops.

3.3 Main fertilizers

Plants need nutrients to grow, these nutrients are absorbed from the soil through the plant's root system. Fertilizers provide the major nutrients but also some other important secondary elements that plants need. Unless the nutrients are replenished, the soil's productive capacity declines with every harvest. Plants must obtain these nutrients from their environment and different sources to grow optimally. The three primary nutrients are nitrogen (N), phosphorus (P) and potassium (K), followed by three secondary nutrients calcium (Ca), magnesium (Mg) and sulphur (S) and other micronutrients (boron, cobalt, copper, iron, manganese, molybdenum and zinc), which can be incorporated into the major fertilizers or be supplied as specialty products.

Nitrogen (N)

Nitrate-based fertilizers are the most commonly used straight fertilizers in Europe. The production of nitrogen mineral fertilizers is based on the Haber-Bosch process. The process means fixing nitrogen from air (atmospheric nitrogen) with hydrogen to produce liquid ammonia. The process uses a catalyst and requires a high temperature and high pressure. The hydrogen as well as the energy to heat the process is generally sourced from natural gas (methane) [15].

Approximately 65 % of the natural gas used in the process is needed as a source of hydrogen for ammonia and the remaining 35 % is used for heating the process itself. Due to improving technology, the energy efficiency of the process has enhanced over time. Globally 450 Mt of nitrogen fertilizers, measured as commercialized product, are produced with the Haber-Bosch process every year.

The main products are nitrate-based fertilizers such as ammonium nitrate (AN) and calcium ammonium nitrate (CAN), which are well suited to most European soils and climatic conditions, and urea and urea ammonium nitrate (UAN) aqueous solution, which are widely used in other parts of the world. Globally, urea is by far the most used fertilizer expressed in terms of nutrient followed by nitrates. Other straight nitrogen fertilizers include ammonium sulphate and ammonium sulphate nitrate, calcium nitrate, sodium nitrate, Chilean nitrate and anhydrous ammonia.

Phosphorous (P)

Phosphorous based fertilizers exclusively origin from mined ore. The process to convert the ore into a fertilizer product is done via a chemical extraction with an acid, into a water-soluble salt. Crushed phosphate rock is primarily converted into phosphoric acid, which is then either concentrated or mixed with ammonia to make a range of products.

The most common phosphate fertilizers are single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), di-ammonium phosphate (DSP) and ammonium polyphosphate liquid. By-products of phosphoric acid production include the fertilizers calcium sulphate or calcium nitrate.

Potassium (K)

Potassium is the third major plant and crop nutrient. Since potash is water-soluble, the production method is mainly based on a purification process of the potassium rock so the muriate of potash (potassium chloride) is separated out of crushed potash ore. This potassium fertilizer may then be further treated with nitric or sulphuric acid to produce potassium nitrate or sulphate of potash.

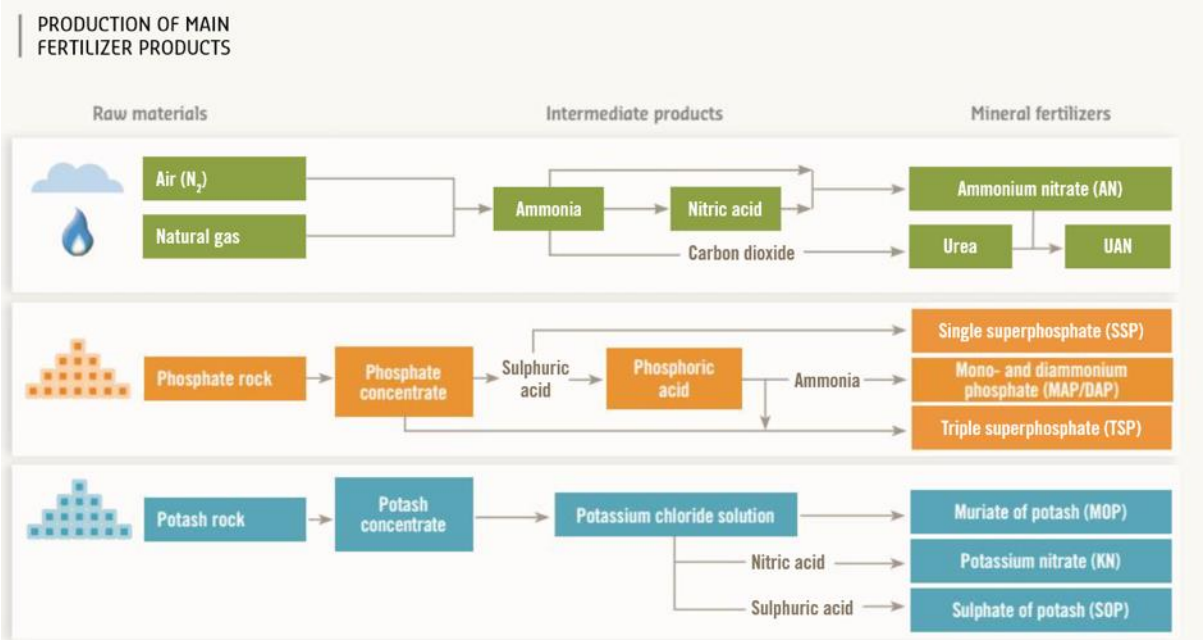
Potassium is also available in a range of fertilizers which contain potassium only or two or more nutrients and include Potassium chloride (KCl), Potassium sulphate (K2SO4) or sulphate of potash

(SOP), Potassium nitrate (KNO3), known as KN.

Three to five per cent of the global annual natural gas consumption is used by the industry to produce N fertilizers. The cost for natural gas represents 60-80 % of the variable input costs for production of N fertilizer. The production of rock-based such P and K fertilizers into a product that can be used by farmers is less energy demanding compared to producing nitrogen and the dependence of natural gas is therefore lower[15].

At the below figure the production process of each of the main mineral fertilizers as well as the intermediate products are presented. The production of ammonia is considered as the most energy intensive process.

Figure 17 - Production of main fertilizer products. Source: Fertilizers Europe



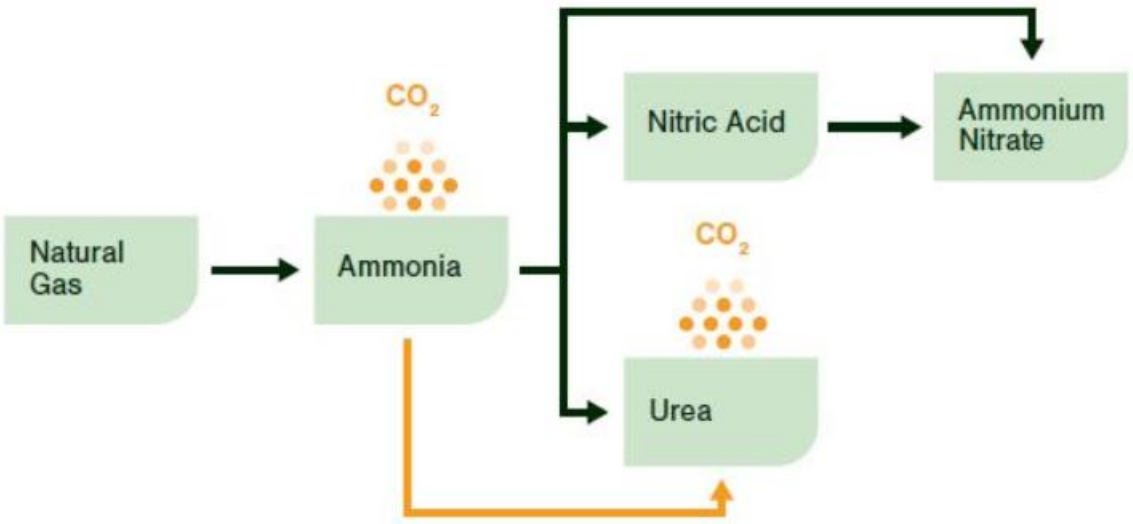
3.4 Ammonia production process

Taking into to account that almost the 75 % of the total European production fertilizers production is N fertilizers and that production of ammonia is responsible for the 30 Mt of the total 35 Mt of greenhouse emissions that produced the fertilizer industry in 2020, it is obvious that ammonia is the dominant emitter. Moreover, ammonia is also used in the production of some P fertilizer so it is the main process that the fertilizer industry is studying and thinking of decarbonization solutions. So, as the main intermediate product used in fertilizers production, ammonia is also the main building block for mineral fertilizers. Ammonia, a basic chemical product, is produced from nitrogen and hydrogen

in the Haber-Bosch process. Nitrogen, in its molecular form, is a readily available substance as it is the main component of atmospheric air. Hydrogen, on the other hand, must first be synthetized, starting from other substances like hydrocarbons or water. As feedstock could be used heavy oil and coal but due to higher cost the most European plants use natural gas. Hydrogen, the desired product of the steam reforming process, may be produced from natural gas by three different chemical processes: Steam Methane Reforming (SMR), Partial Oxidation (POX) and Auto-thermal Reforming (ATR). Hydrogen can be also produced from water through electrolysis process [18] but SMR is the main process that is used in Europe since it is the most efficient and economically available technique of hydrogen production at this time.

Ammonia production is carried out in two stages, the SMR stage for the production of hydrogen, which is the feed material of hydrogen production and the Haber-Bosch stage where hydrogen produced and nitrogen react, producing ammonia.

Figure 18 - Current ammonia production process. Source: Fertilizers Europe



SMR process

Through SMR, heat and steam are used for **the conversion of natural gas to grey H_2** with an inevitable production of CO_2. In this process, pre-treated natural gas is fed with steam to a primary reformer, producing synthesis gas with the required heat for this endothermic reaction being produced by burning part of the natural gas input. In the secondary reformer, air is added to the process in order to convert the residual methane and at the same time to introduce to the process the nitrogen required for the synthesis of ammonia by removing the oxygen [20].

Steam-methane reforming reaction:

$$CH_4 + H_2O (+ \text{heat}) \rightarrow CO + 3H_2$$

The synthesis gas (CO and H_2) feeds a high temperature shift reactor (HTS) and subsequently a low temperature shift reactor (LTS), where most of the carbon monoxide is converted in the water gas shift reaction, to CO_2 and H_2.

Water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 (+ \text{small amount of heat})$$

The product is purified by removing CO_2 through one of several methods: chemical absorption, physical absorption, or pressure swing adsorption (PSA)[18]

Haber-Bosch process

The next step for the production of ammonia is the Haber-Bosch process, which is applied for more than 90% of world's ammonia production.

In this process, hydrogen produced and nitrogen react in an exothermic reaction, over an iron catalyst to produce ammonia. The hydrogen required for the process can be obtained from SMR or electrolysis of water. Nitrogen for the reaction, is already part of the synthesis gas in the secondary reformer of the conventional process. In situations where hydrogen is not produced via SMR, an air separation unit (ASU) is required to provide the required nitrogen from the air. Nitrogen and hydrogen are compressed to pressures between 120-220bar and sent to an iron oxide catalytic reactor operating at temperatures of 400 - 450°C. The product is gaseous ammonia which is cooled and liquefied at temperatures of -10°C to -25°C [18].

$$N2+3H2 \rightleftharpoons 2NH3$$

The liquefied ammonia acts as feedstock to produce intermediate products like nitric acid (HNO3), and downstream products like nitrogen fertilizers (such as ammonium nitrate, urea, UAN, or CAN) and NPK (nitrogen, phosphorous and potassium) fertilizers.

3.5 Energy and GHG emissions

The European fertilizer industry over time has significantly reduce the CO_2 emissions due to the implementation of abatement technologies and due to the energy efficiency improvements, however still emits considerable amounts of CO_2 and remains an energy and emission intensive industry. In 2020 fertilizer industry emitted around 35Mt CO_2 and ammonia was responsible for 30Mt of them.

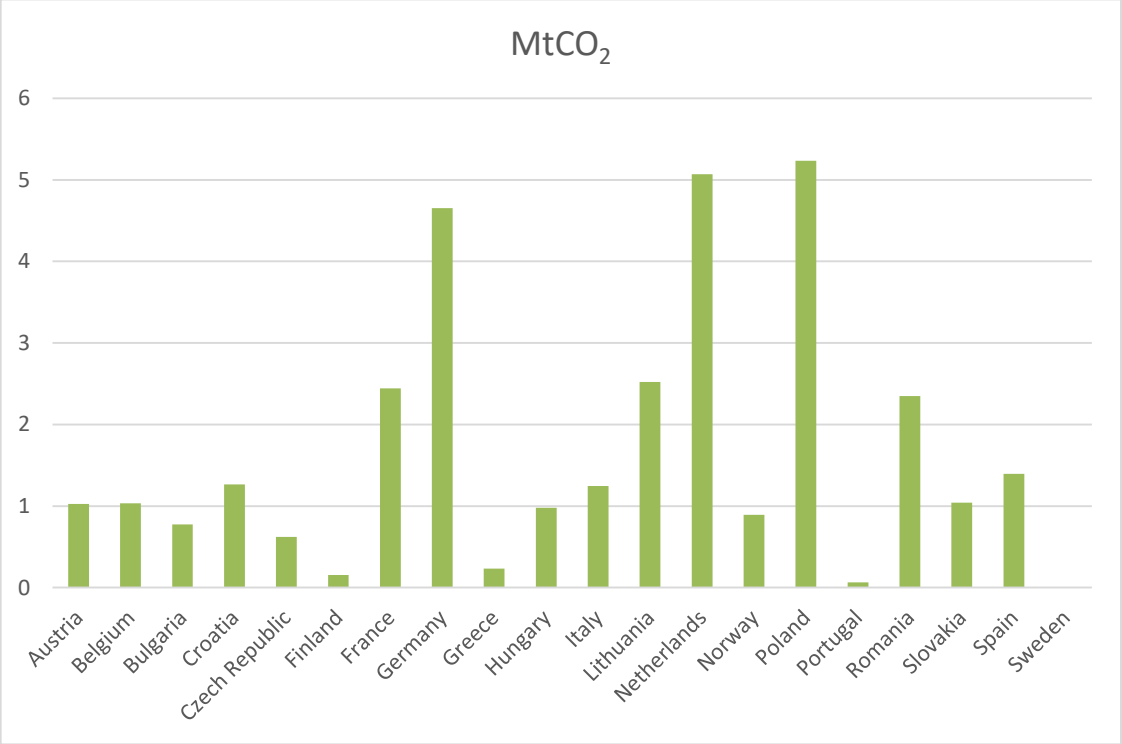
The GHG emissions produced along the fertilizers production value chain are mainly due to the



combustion of fossil-based energy sources but also CO_2 and CH_4 are emitting from feedstock mining (natural gas), fossil-based electricity heat consumption and the steam reforming process. Approximately 65% of the natural gas is used as the raw material for sourcing hydrogen, with the remainder employed to power the production process. Finally, N_2O and CO_2 are emitted during agricultural application of fertilizers products [18].

The hard-to-capture CO_2 emissions from the reformer unit in the SMR process usually contribute the most to GHG emissions, followed by CO_2 from the combustion of fuel for steam generation [21].

Figure 19 - EU CO_2 emissions ($MtCO_2$) per country. Source: list of EU ETS companies, (https://re4industry.eu/eiis- interactive-map/)

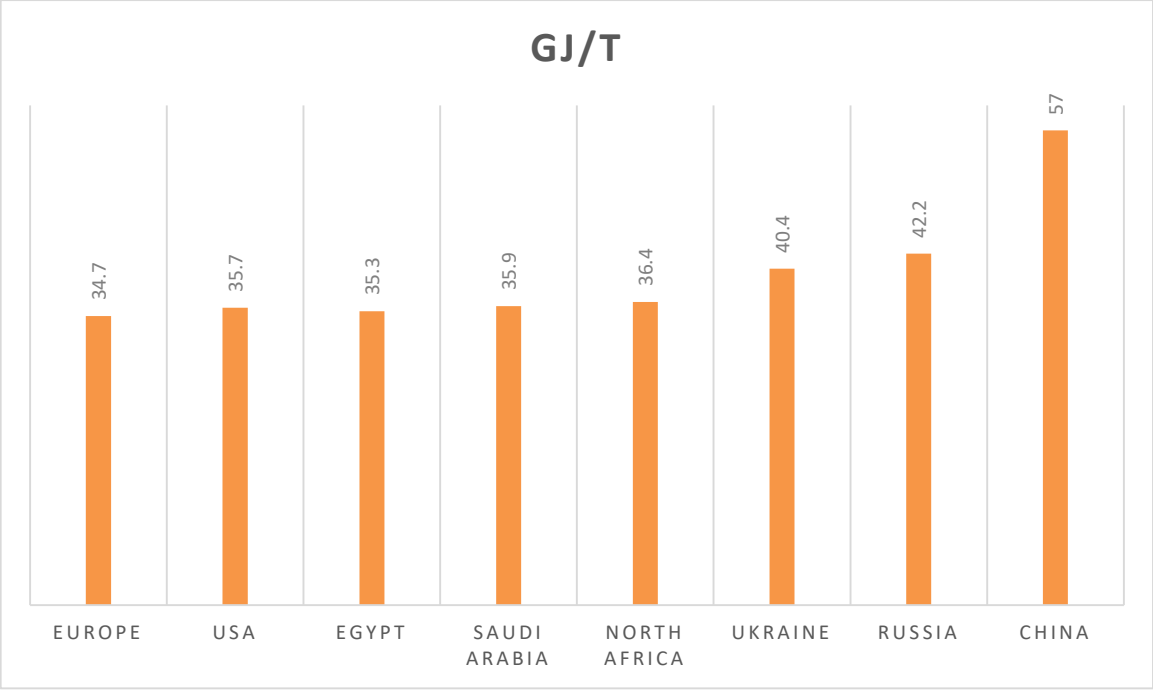


It is estimated from the International Fertilizer Association that the fertilizer industry represents 2.5% of the global GHG emissions, including 1.5% related to fertilizers use [22].

The average energy efficiency for European fertilizers production plants is higher than the global average due to the use of relatively modern technology and reduced use of coal as main energy supply. The main driver for this is Europe's strict environmental legislation that pushed the past few years the European industry to invest steadily in order to increase its efficiency and reduce GHG emissions.[23]

As a consequence of this innovative advancements in technology, the European fertilizer industry's ammonia plants are among the most energy efficient worldwide, with the lowest GHG emissions, even though the production of nitrogen fertilizers, which reaches the 75% of total production, is characterized by high carbon-intensity. On average, 1.9 t of CO_2 are released on-site during the production of one ton of ammonia during the conventional method [18]. Its nitric acid plants are also equipped with advanced greenhouse gas emissions reduction technology.

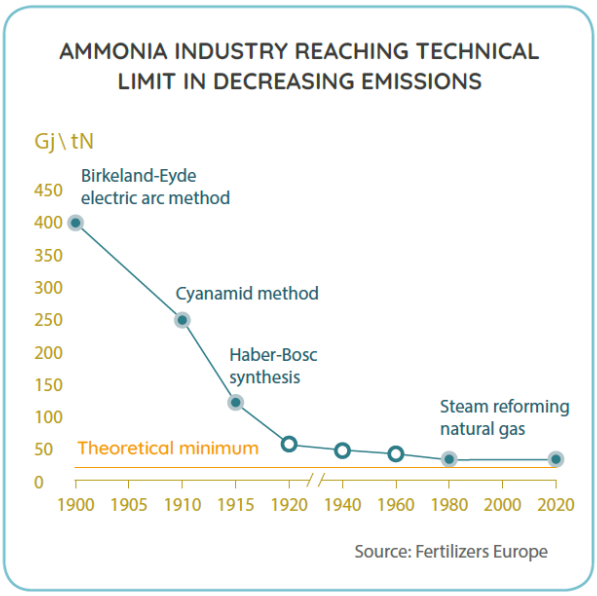
Figure 20 - Energy consumption (GJ per ton of product) in ammonia plants Worldwide (regional averages, 2011) [10]



3.6 Potential alternatives and the role of ammonia

The European fertilizer industry has succeed the last decades to drastically improve the energy efficiency of its production (Figure 10) so it is at a point where further investment in current technology is unlikely to take place. It is necessary the fertilizer industry to reinvent itself and go beyond current technology.

Figure 21 - Fertilizer industry reaching technical limit in decreasing emissions. Source: Fertilizers Europe [24]



So, despite the enormous strides made by the industry in recent years in reducing emissions, current production methods still remains energy intensive. In particular SMR even though it is the least carbon intensive, still generates large amounts of CO_2. Through SMR, ammonia, the starting point for all mineral nitrogen fertilizers, is producing, forming a bridge between the nitrogen in the air and almost half of the food we eat. About 70% of ammonia is used for fertilizers, while the remainder is used for various industrial applications, such as plastics, explosives and synthetic fibres. So, ammonia makes an indispensable contribution to global agricultural systems through its use for fertilizers. Its production is an emissions and energy-intensive process, relying on fossil fuels, mainly natural gas with the global ammonia production accounts today for around 2% (8.6 EJ) of total final energy consumption [25].

Production of nitrogen fertilizers is based on high temperature 'cracking' of natural gas which is the raw material into hydrogen and CO_2. Hydrogen is then combined with nitrogen from the air to create ammonia. Ammonia then, through some other process produces a range of fertilizers such as urea whose production also requires large amounts of energy [25].

Due to all the above facts the fertilizer industry is focusing on the decarbonization of ammonia production which is the main contributor to energy consumption and CO_2 emissions. The potential solutions are categorized in two main options. The first one focuses on the reduction of the CO_2 emissions and the second one has as goal the CO_2 avoidance.

The first low-carbon alternative involves the underground storage of the CO_2 that is generated during the production process of ammonia. The second alternative solution is focusing on alternative

sources of H2 for the Haber-Bosch process. The electrolysis of water (yellow and green hydrogen and methane pyrolysis (turquoise hydrogen) are the basic potentials for the decarbonization of fertilizer industry. Regarding the labelling of the different “types” of ammonia, ammonia’s color is corresponding to the color of its hydrogen feedstock.

Blue hydrogen replicates the process of conventional hydrogen (grey hydrogen) production, with a difference in the application of CCS technology. Compared to grey hydrogen, the emitted CO_2, once captured during the steam reforming process, is compressed into a liquid, transported by pipeline, ship, or road tanker and stored underground.

Green and yellow hydrogen are produced in an electrolysis process, with the only difference being the source of electricity. While green hydrogen is produced exclusively from 100% renewable (wind, solar, hydro, geothermal, biomass, etc.), yellow hydrogen proceeds from grid electricity which is not necessarily green, due to the contribution of fossil fuels to the electricity mix. The replacement of hydrogen from SMR with green hydrogen, has the advantage of not emitting CO_2 nor other GHGs. There are no direct (scope 1) emissions (since water H2O, not methane CH4, is used as source for hydrogen) and given the use of green electricity, there are also no indirect (scope 2) emissions [18].

Turquoise hydrogen is produced through the technology called methane pyrolysis. During this thermal process, methane, under the application of high temperatures (700-1800 ºC is splitting into its elements, namely solid carbon and gaseous hydrogen. Unreacted CH4 is separated from H2, and recirculated to the reactor [26]

Finally, hydrogen can be obtained from **biomass**. The main thermochemical processes for the hydrogen production are gasification, pyrolysis and combustion. The disadvantages of this option are that the hydrogen content in biomass is low and the technologies are still immature. These facts make these technologies economically uncompetitive compared to the use of natural gas reforming [18]. Combining hydrogen production from biomass with CCS could, however, be an option to create so-called “negative emissions”, which may have a role to play in the future [21]. Alongside hydrogen can also be synthetized from biogas, which is produced from the anaerobic digestion of energy-rich organic biomass. Firstly, biogas is converted to biomethane at natural gas quality, and subsequently undergoes the SMR process to obtain hydrogen, so the production of hydrogen from biogas depends on the methane content of biogas which is about 25% in mass. Another biogas option, which is in testing phase is the use of a catalytic membrane reactor. During this process the reactor integrates hydrogen production and separation in a single step, leading to over 70% reaction conversion at 500-550°C [27]

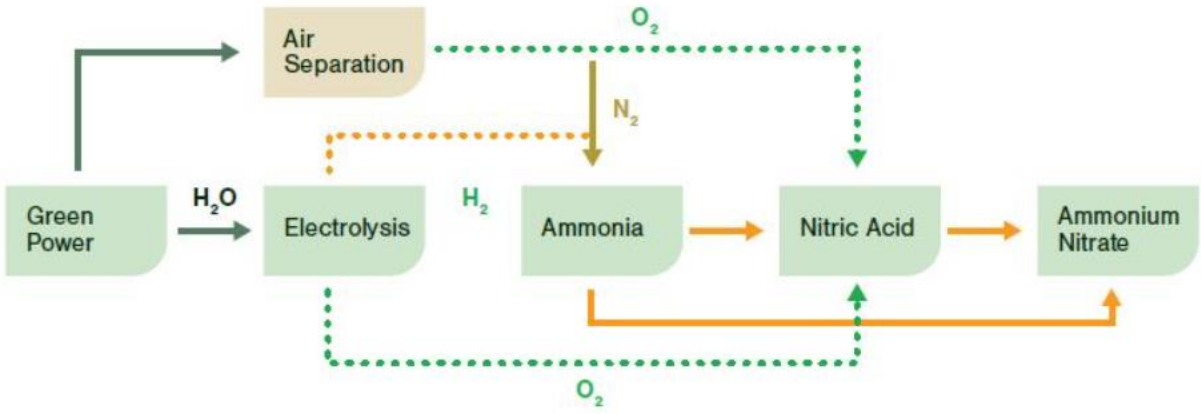
These technologies, however, are currently not economically justifiable. However, by 2050, under



the right conditions, ammonia production could be based on decarbonised sources of energy, using alternative sources of hydrogen and electrolysis based on renewable energy.

To this direction, **"green ammonia"** will play a fundamental role in the decarbonization of the industrial sector. The technology and the share of renewable energy used to produce ammonia will be crucial for the overall climate impact of the production of nitrate-based fertilizers [19].

Figure 22 - "Green ammonia" production process. Source: Fertilizers Europe



Today ammonia is mostly associated with fertilizers manufacturing, however, in the future, ammonia produced with zero or near-zero carbon footprint could also help decarbonize other sectors, like energy and transport. Due to its high energy density and ease of storage and transport, ammonia is a technologically superior and more energy efficient carrier of hydrogen than hydrogen itself. Therefore, it can be used as direct or indirect fuel for high temperature heating, for power generation and in long range maritime transport combustion engines or even to automotive sector or fuel cells drive [28].

With a share of 50%, the ammonia industry is one of the biggest producers and users of hydrogen in Europe and considering that the ammonia molecule is among the best alternatives for the mid/long-term storage of electricity in the form of chemical energy, fertilizer producers could be frontrunners in scaling up the production of renewable hydrogen.

3.7 Challenges and policy recommendations

The EU fertilizer industry is placed in the forefront of the transition to climate neutrality by 2050, with an ambitious mid-term target to reach -55% GHG reduction versus 1990 by 2030, has already made tremendous improvements in its processes using almost exclusively natural gas and applying the SMR – the most efficient process used in large scale-. However, the challenges and barriers are many and the existence of a short and long term vision, with effective measures is required in order

to remain the EU fertilizer industry competitive.

One of the major challenges that the fertilizer industry has to cope with are the consequences of the EU ETS. Today, the European fertilizer industry's competitiveness is already affected by the EU Emissions Trading System (ETS) and the further decarbonisation of the sector will increasingly expose the industry to the risk of **carbon leakage**. Current measures under EU ETS are not enough to limit European fertilizers sector's genuine exposure, because imports of fertilizers from countries that have a higher carbon footprint have increasingly substituted domestic EU product. This, has as a result the increase of imports from 20% to 30% of EU consumption over the last decade and eventually a net increase of GHG emissions globally.

Table 1 - Carbon leakage indicator. Source: Fertilizers Europe

	Trade Intensity	Emission Intensity (kg CO_2/EUR)
Non-Ferrous metals	4%	0.2
Organic basic chemicals	49%	2.2
Inorganic Basic chemicals	54%	3.0
Paper	28%	3.0
Fertilizers	32%	7.6
Steel	26%	8.3
Refineries	26%	12.5
Cement	10%	24.2

Due to these differences in climate ambitions between the EU countries and the trading partners, the European Commission made a proposal known as **Carbon Border Adjustment Mechanism** in order to ensure that the price of imports reflects their actual carbon content. In line with the mechanism, importers of fertilizers into the EU will pay an amount equivalent to the cost of the carbon (above the benchmark) that is generated during its production. In this way, the CBAM combined with EU ETS free allowances would create a level playing field for EU fertilizers producers while, at the same time, encouraging third country producers to decarbonize their production. At the same time the mechanism should include equivalent measures in order to secure the competitiveness of the exports.

Towards this transition as described before, the green ammonia will play a significant role. In order to make the **green ammonia an appealing market** some measures need also to be taken.



Low-carbon, abundant and competitively priced hydrogen is a pre-condition for green ammonia to become competitive versus current technology. The first step is the creation of potential markets which rely on the flexibility of green ammonia such as the green chemicals, the energy storage, the low carbon fertilizers and the transportation where green ammonia holds the promise of a 95% reduction in maritime emissions by 2035 [24].

The most challenging aspect facing green ammonia however is the **cost of production**, which is currently two to four times as expensive as that of conventional ammonia. **Financial support**, especially for **early movers** investing in capital-intensive green ammonia infrastructure, will be vital and these higher costs will also need to be spread across the whole value chain and not just borne by the producer. Also, since the production of green ammonia is an electro-indecisive process (electrolysis), **green electricity prices** should be reduced economically of the goal is to be viable and competitive.

Most of the potential technologies that where mentioned above, ether near-zero-emission (CCS, methane pyrolysis) or net-zero emission (electrolysis) technologies **are not economically viable** yet and so, not available in commercial scale. To overcome this obstacle the Green Deal should encourage **economically investment in large scale demonstration projects and knowledge build-up**.

Regarding the CCS technologies will be important the implementation to be proximate to storage location or otherwise if the captured CO_2 needs to be to transported, infrastructure should be available. Finally, socio-political acceptance for this technology will play a key role, so that not all production plants in Europe will have the opportunity to use it. Additionally, for the **transportation of green hydrogen infrastructure adjustments** are needed otherwise green hydrogen must be produced on-site.

Focusing on the fertilizer industry the main actions are the establishment of a transition plan, the acceleration of R&D in near-zero-emission technologies and the development of supporting infrastructures. For this transition to succeed, **collaboration** between governments, producers, consumers, technology suppliers, financial institutions, researchers, non-governmental organizations and others is required.

Governments bear a heavy burden of responsibility, they should establish a strong and stable market signal for emission reductions aligned to the EU climate, energy, and industrial strategies. In consultation with the industry, they should develop sustainable transition plans for ammonia production, which could be supported by researchers and NGOs. Governments is also important to support the transition through direct grants and other subsidies mainly to R&D, first-of-a-kind



commercial projects and shared infrastructure and of course create sustainable finance taxonomies environment for the fertilizer industry.

As it is clear the key word for this transition is the financial investment. Increased **R&D for near-zero technologies** will contribute to the reduction of the technology costs and will help the technology choices to be better suited to regional circumstances. The risk and the financial challenges of the manufactures are tremendous since the cost of near-zero technologies are from 10% higher to more than double, increasing the production costs and injuring this way their competitiveness. The R&D, therefore, will be helpful with the risk and uncertainties that causes the implementation of such technologies. Apart from the funding on R&D, **financial support should also be given in the existing and new plants, and in supporting infrastructure**, however, investment in new capacity should be focused in near-zero-emission technologies. Financial institutions can promote investment in low-emission technology deployment among investors through sustainable finance schemes, by issuing green and transition bonds and working with governments on blended finance mechanisms and sustainable finance taxonomies [25].

Last but not least the focus on **circular economy** should always remain high on the agenda. Recycling and symbiosis will play their role closing the loop in material and energy flows during manufacturing. So the intention of recycling and symbiosis is to avoid waste by recycling products and using them as input for other production processes. The main object in both of them is to optimize resource use, close material loops and minimize emissions, thus reducing and possibly even eliminating the dependence on non-renewable energy resources. By including recycling and symbiosis in the production, sustainable production and competitiveness is fortified, so it is important the focus to be on the creation of industrial networks on local, regional and European levels [29]. And finally in the frame should be the optimization of the **efficiency of nitrogen fertilizers** and ammonia products which could significant reduce the sector's emissions.

According to Fertilizers Europe, a combination of policy solutions is needed to enable the transition to a climate-neutral economy by 2050 while keeping fertilizer industry competitive. The main targets should be [30]:

- Low-carbon and competitively priced energy and feedstock
- Infrastructure to transport low-carbon resources
- Infrastructure for CO_2 management and avoidance
- Funds to finance the transition



For closing, as it was mentioned before it is necessary the fertilizer industry to reinvent itself and go beyond current technologies. So, “going beyond” means major developments in energy infrastructure, price competitiveness of green energy, scientific breakthroughs and markets for low carbon products.

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RE4iNDUSTRY

100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

D3.1 - EIIs Sector Status in Europe

Glass industry

Authors: Alejandro Fresneda, Alessandro Carmona

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Abbreviations

Abbreviation	Definition
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CFCG	Continuous Filament Glass Fibre
EAF	Electric Arc Furnaces
EII	Energy Intensive Industry
EU	European Union
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
UK	United Kingdom



1. Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe, focusing on the **glass industrial sector**. The report aims to capture the current status of the glass sector in Europe, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonisation.

Following this introduction, Chapter 2 gives a general overview of the glass sector and its importance for the European and global economy.

Each of the Chapters 3 to 6 focuses on a specific glass subsector or product. This selection englobes the main industrial activities in the glass industry, concerning production as well as the highest overall energy consumption. For the glass sector, the report provides information on the current usage and importance, main production processes, energy and GHG emission profile, as well as potential alternatives for cleaner production processes or for mitigating their climate impact.



2. The Glass sector

Glass still represents one of the largest used materials in manufacturing, building and consuming processes, significantly enabling light-weighting products and superior quality glazing. But moreover, glass also represents a 100% recyclable material which contributes to a sustainable society that meets green principles of circular economy.

Main findings highlight the use of high-temperature melting furnaces as various heat-intensive equipment for processing stages accounting 1% of total industrial energy share [1]. Most furnaces are fed with natural gas or with fuel oil as standby fuel) or by electricity, considering processes carried out by electrification alternatives.

The glass sector comprehend the following main products (Figure 1) [2]:

- **Container glass**: The largest sector of the EU glass industry. It accounts around 62% of European glass production. Mainly for packaging products as bottles and jars and for different sectors as food, cosmetics, perfumery at a European or at a global wide costumer level.
- **Flat glass**: It represents the second largest glass sector of glass industries, and it accounts for nearly 29% of total European glass production. Residential, automotive, and commercial construction applications are the main markets (these are windows, tabletops, mirrors, among others). Moreover, flat glass has also innovative applications specially interesting for renewable energies and sustainability markets as in solar energy photovoltaic and solar thermal panels or for urban / domestic furniture and greenhouses.
- **Fibre glass:** Continuous filament glass fibre (CFCG) production contributes with the smallest share in glass sector (2% in terms of tons). CFCG is mainly used for weight-lightening reinforcement material (composites) which enables special applications covering automotive and aerospace sector, energy, agriculture, construction, communication, electrical and electronic as well as sport and leisure.
- **Domestic:** this sector covers the manufacturing of glass tableware, cookware and ornamental material and items such as drinking glasses, bowls or vases.
- **Special glass products**: Regarding special glasses, they represent a small share in total global glass production for high added-value products aiming intense-technological content applications such as lighting glass, laboratory glassware, high-resistant glass, optical or ophthalmic glass and extra thin for electronic industries.



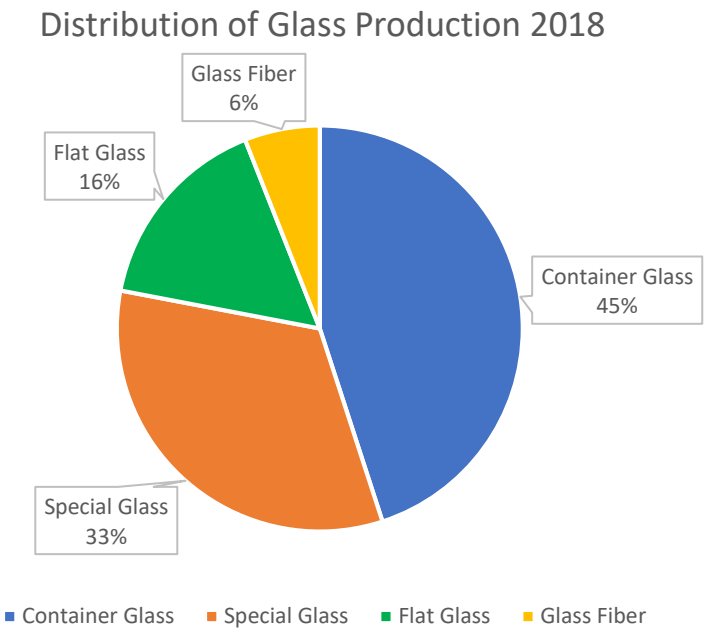


Figure 1- Global Glass Manufacturing Market

Glass manufacturing sectors are considered an energy-intensive industry (EII) and thus, energy is the largest operational costs that impacts on its activity. Moreover, due to their share and interlinkage with a variety of other main industrial sectors, it is obvious that glass has an economic and strategic importance for Europe.

2.1 Overview of European glass sector

The European glass market global share is consolidated as the biggest producer with one third of total world production. Main findings address the European glass industry for its quality, technological innovation capacity [3]:

- **Competitiveness:** Glass industry in Europe is represented by large-EU-based companies. The production process is energy intensive, and the manufacturers must face high start-up costs and tied distribution channels.
- **Innovation**: Research and development projects have resulted in improvements to energy savings and environmental protection enabling first steps to a transition from fossil to non-fossil energy, and glass fibre substituting metals and wood through composites.
- **Export and import:** 80% of produced glass is traded within the EU

The production of glass by EU 28 in tonnes reported by Eurostat in 2020 [4] is categorized in 22,331,000 tonnes in container glass, 10,773,000 tonnes in flat glass, 1,132,000 tonnes



in domestic glassware, 853,000 tonnes in CFCG and 542,000 tonnes in special glass (Figure 2).

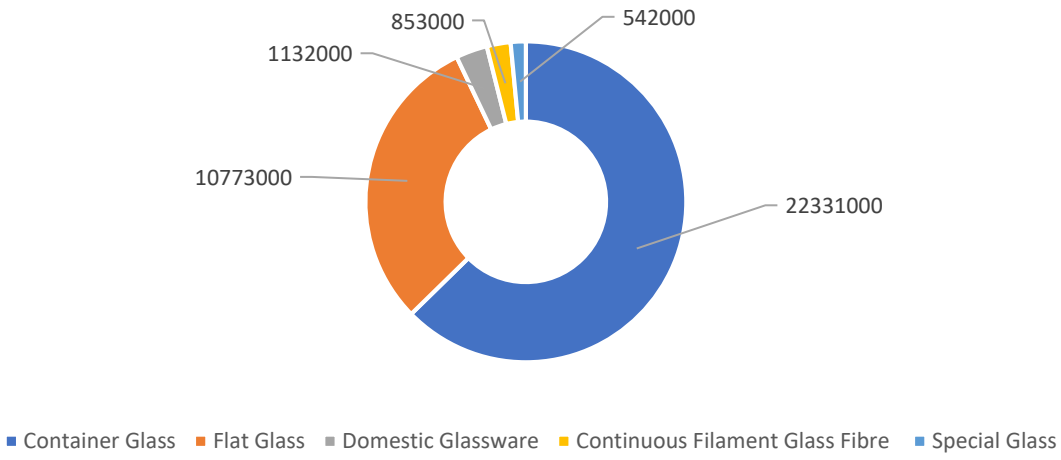


Figure 2: EU Glass tonnes produced (Source: Eurostat)

Overall numbers estimate 186,000 jobs generated in the EU by 2020, including almost 44,000 direct jobs at glass manufacturers.

Regarding UE 27 data, those overall numbers determinate 6,100 jobs per million tonnes of glass (192,4 tons of glass produces per employee, direct, indirect and induced jobs) ([5].

) [5].

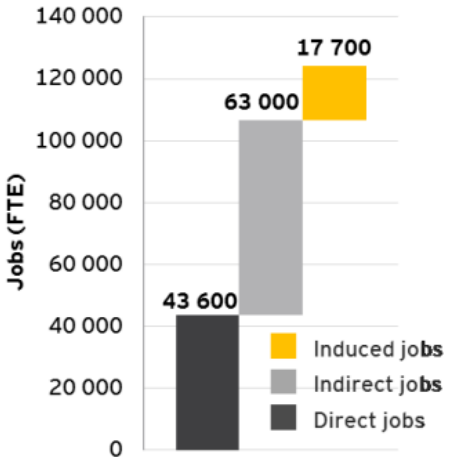


Figure 3: Direct, indirect and induced jobs generated in the EU by the container glass sector in 2012 (Source: FEVE, 2015)

Employment creation is enrolled by 162 glass producing plants operating in Europe (Figure 4), reaching 20.3 million tons of glass bottles and jars (averages of 55.000 tons per day). Glass production is present in most of the EU member states with the largest presence in

Germany (32 plants), followed by Italy (27), France (24), Poland (18), Spain (16) and UK (12).



Figure 4: Container glass plants by country (Source: FEVE, 2011)

Over the period 2003-2012, the total investment at the EU27 level is estimated between € 500 million and € 610 million per year on average. The aim for these funds was to upgrade the plants, such as substitution of fuel to gas for the furnaces and investments in air emission filters, implying higher energy efficiency and lower CO2 emissions (Figure 5).

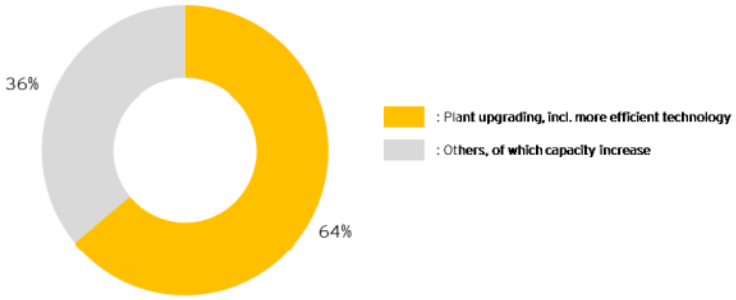


Figure 5: Average annual investments (CAPEX) (Source: FEVE, 2003-2012)

Finally, several challenges are listed to overcome by the glass European industry during the next decades:

- Economic and supply chain **crisis** leading to severe impacts in industrial activities
- Novel **restrictions** aiming to circular transition and sustainable economy.

- Trading, **competition**, energy prices and substitution by other products.

2.2 Energy consumption and GHG emissions

Glass is an energy-intensive sector; hence, energy represents one of the largest operational costs in glassmaking. However, it is still hard to find clear and recent data from energy consumptions and emissions of the European glass industry, as there exist no available sources of public data. The following brief analysis is based on data from 2017-2015 period and of several geographic zones. Additionally, the container and flat glass subsectors have been identified as the largest emitters with almost 80% share both combined (Figure 6).

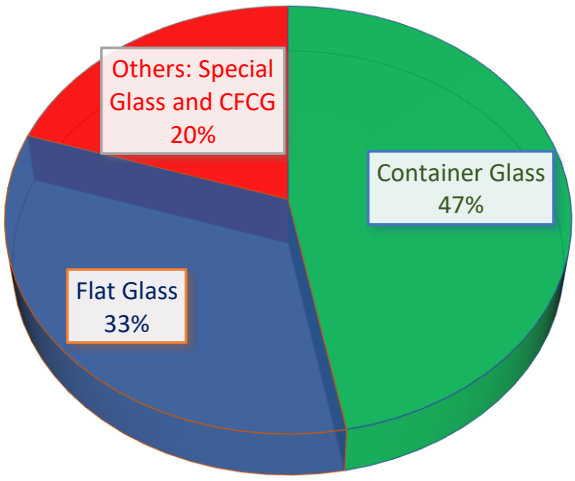


Figure 6: Glass subsector emissions share

Several authors achieved to determinate overall emissions of glass subsector in EU 25 by 2007 [6] where direct CO_2 emissions and fuel consumption are distinguished from indirect emissions derivated from electricity production/consumption.

Overall CO_2 emissions of the European glass industry by 2007 reached 21.19 Mt CO_2 thereof specific emissions from combustion where 16.89 Mt CO_2. Some data can be tracked via EU ETS [7] establishing an increase of total emissions to 21.7 Mt by EU 27 (Year of emissions: 2019).

Furthermore, indirect emissions typically derivate from electric boosting in furnaces melting processes and downstream activities, which amount 5.7 Mt by EU 25 and increasing overall direct and indirect numbers up to 27.5 Mt CO_2 emissions in EU 27.

The US Environment Protection Agency tracking application counts 7.4Mt CO_2 during 2020 associated to the Glass Industry in the United States [8].

However, other different sources differ from those numbers, whereas determination of overall quantities show as far as 60 Mt CO_2 emissions globally in 2007 and18 Mt by 2019 at European level [9]. It is likely that numbers might also comprehend different or additional steps of downstream glass sector supply chain for their analysis.

Specific data are shown for UK glass industry, where clear reduction of absolute and relative emissions is shown for the last two decades, due to more efficient installations furnaces and various decarbonization options as demonstrate in Figure 7 [10].

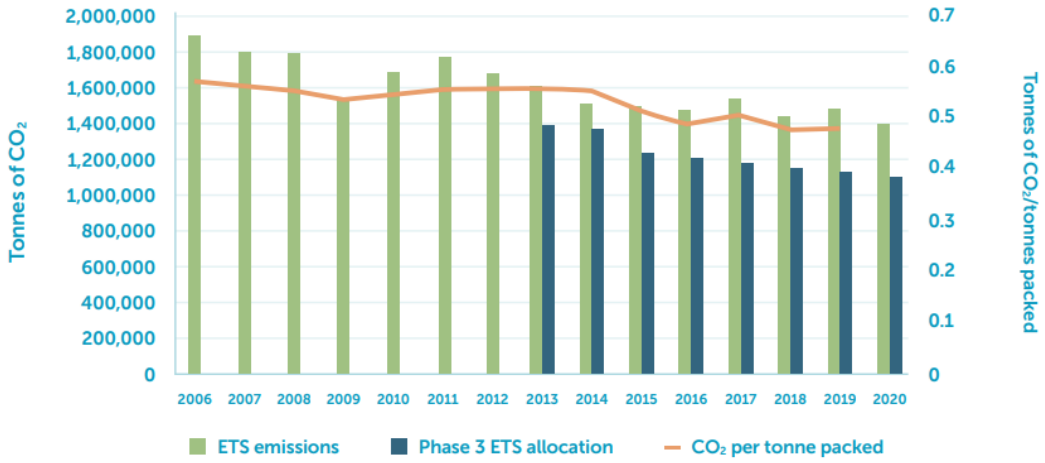


Figure 7: UK Glass Industry emissions from 2006-2020 (Source: British Glass, 2015)

Regarding energy consumption, fuel and electricity consumptions are not specified in any of the available public sources. Thus, energy consumption by the glass sector has been assumed from emissions data. Table 1 compiles those data on energy consumption.

Table 1: Primary and final energy consumptions EU25 and EU27

European Union	Fuel Consumption (PJ)	Electricity Consumption (PJ)	Total Final Energy (PJ)
EU-25	284.4	59.2	343.6
EU-27	291.6	60.4	352.0

As a comparison, energy consumption data from the US glass industry in 2010 are shown in Figure 8. The available information shows that the glass manufacturing sector is mainly fueled by natural glass (75%). Overall consumptions reach up to 200 trillion Btu (equivalent to near 211 PJ). The bulk of energy is told to be consumed by natural gas combustion to heat furnaces in melting steps.



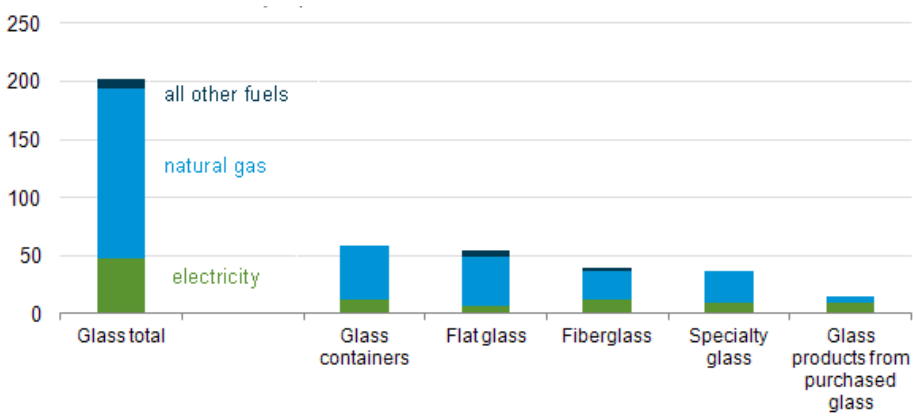


Figure 8: Energy consumption in glass manufacturing by fuel (trillion British Thermal Unit, btu) (Source: Energy Information Administration U.S)

Historical data show that the glass industry sector has decreased its emissions and energy consumption in the last 50 years with a 69% reduction of CO_2, where the main sources of emissions are indeed high-temperature heat for melting procedures (75-85% of total emissions) and emissions from carbonates decomposition (15-25% of total emissions) [11].

2.3 Energy efficiency and decarbonisation innovations

Currently, the identification of enablers, barriers, and technical options to decarbonize various stages of glass manufacturing is a priority within the sector. Figure 9 shows some of the identified processes where innovation might have an impact on the glass sector to implement decarbonization actions.

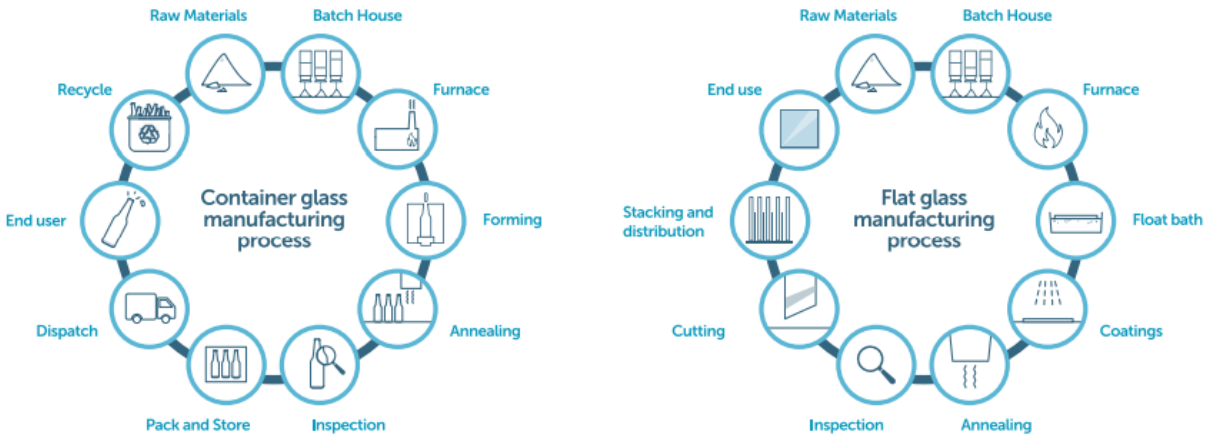


Figure 9: Container and flat glass manufacturing process (Source: British Glass, 2015)

It is worth noticing that the glass manufacturing processes highly depends on the final

product. Most of the manufacturing glass processes have a common origin: glass first needs to be melted. Raw materials (different types of sand and minerals and/or recycled glass) are mixed and charged into a furnace where they are melted at imperatively high temperatures around 1,500°C. Molten glass is taken out of the furnace, shaped and let cool down. Some of the main barriers, enablers and decarbonization options are summarizes in Table 2 [12].

Table 2: Enablers and barriers to decarbonize glass industry

Enablers
• **Proven and financially viable technologies**
• **Increasing lifespan of equipment**
• **Regulations encouraging energy efficiency in downstream sectors**
• **High and increasing energy prices**
• **Strong recycling infrastructure**
• **Commitment by top management to an environmental policy or climate change strategy**
• **Stable energy efficiency and carbon regulatory framework**
• **Legislative compliance**
• **Replacement of obsolete equipment**
Barriers
• **Long payback periods and high costs**
• **High and fluctuating energy prices**
• **Uneven playing field with overseas competition**
• **Retrofit capability**
• **Lack of capital**
• **Chemical and process efficiency limitations**
• **Low demand risk**

Recommendations inside the glass sector aiming emissions reduction and addressing decarbonisation technologies are common among the available literature (Table 3). However, their financial viability and technical feasibility needs further research:

Table 3: Decarbonization innovation technologies

Novel technologies
• **Energy efficiency improvements in terms of fuel furnace consumptions**
• **Waste heat recovery to pre-heat combustion air and raw materials, or electricity co-generation**
Combustion innovations
• **Oxyfuel combustions**
• **Introduction of liquid biofuels (biodiesel and HBO)**
Reduce combustion emissions

• **Electric Arc Furnaces (EAF) rather than gas fired furnaces**
• **Hybrid furnaces running on multiple fuels and electricity**
• **Study of the feasibility of hydrogen to run glass furnaces**
Circularity
• **Increased cullet uses to produce new glass (waste to material)**
• **Calcined raw materials as CaO to substitute carbonates reducing CO2 emissions**
• **Carbon capture, utilization (CCU), or storage (CCS) identify as the most potential short-term carbon neutral technology (CCUS)**

From Table 3 it is obvious that all different glass industry subsectors converge at the upstream the value chain: the glass-melting step. As most of the decarbonization initiatives and projects are focusing on this step, it should be understood that the different technologies and innovations presented during the following chapters might be applied to almost all of the different glass subsectors.

Gaseous, liquid, or solid fuels are used for combustion with any oxidant (air, oxygen or mixtures) in combination with more or less electric boosting, maybe as a hybrid furnace, to melt and fine the glass. The flue gases from combustion, as well as the CO_2 emissions from the batch materials are collected and withdrawn in a flue gas channel.

In order to achieve a closed CO_2 circuit loop, the cleaning device that separates the CO_2 of the flue gases from other gaseous components and solid particles is the first asset. Some useful technologies for this could be a combination of a cooling trap and a baghouse filter or other similar technologies. The specific requirements and characteristics of flue gases originating from a glass melting furnace have to be considered when thinking about the closed CO_2 loop.

Waste heat recovery is a simpler strategy to lower carbon footprint of glass manufacturing. The exhaust heat of the waste gas of the furnace can be used within process steps that need higher temperatures or can be fed to a local district heating grid.

Electric power is needed for all steps, and it could be introduced as the primary renewable, CO_2 neutral energy source. The glass melting furnace uses electric power for electric boosting or for hybrid operation modus.

On the other hand, more complex and innovative technologies enhance the glass industry decarbonization, considering carbon capture & use (CCU) with hydrogen to produce renewable fuels.



The current objective is to seek efficient technologies for every step process, with both, low investment, and maintenance cost, and have enough technical maturity.

3. Container glass

3.1 Introduction

Container glass is specifically produced for bottles, bowls, jars, or other packaging items for storing food and/or beverages. Its chemical composition is mainly boron trioxide and silica as main components, but it may contain as well lesser amounts of some metals such as magnesium oxide, calcium and sodium oxide. Container glass markets is constituted by two different sectors: Borosilicate-based glass (Type I) and soda-lime-silica-based (Type II).

While borosilicate-based glass shall exhibit properties as a very low coefficient of thermal expansion (approximately 3×10^{-6} per Kelvin at 20 degree Celsius), excellent chemical stability and thermal shock resistance, soda-lime glass has a better workability, which can be softened and reused multiple times. Together with its high melting temperature, makes it suitable for main container glass applications

- Food & beverages
- Pharmaceutical
- Packaging
- Other end-use sectors

On the other side, due to a higher property performance of borosilicate-based glass, it is able to satisfy several more requesting sectors as construction of reagent bottles and flasks as well as lighting, electronics and cookware.

Overall glass container market was value at $82,210.6 million in 2020, and is projected to reach $155,926.6 million by 2030, growing at a CAGR of 6.7% from 2021 to 2030. [13]

In fact, container glass seems an unbeatable option for packaging, and the increase in demand of food & beverages, and pharmaceutical sector are boosting the market growth. Nowadays, disposable incomes and busy lifestyles are also highly contributing to this growth. R&D activities are also boosting the demand of glass-based flasks and tubes for laboratories, industries and other end use sectors (Figure 10)





Figure 10: Glass Bottles and Containers Market Growth Rate 2021-2027 (Source: Mordor Intelligence)

Main players on this market are represented by big-cap companies which are well stablished on global glass manufacturing. Industries as Amcor PLC, FrigoGlass, Owens Illinois Glass Inc., Consol Glass Pty Ltd., Vitro, Vidrala, Hindusthan National Glass and Industries Ltd., Gerresheimer AG, DWK Life Sciences GmbH, and Toyo Glass Co. Ltd.

3.2 Production process

First, operating facilities and batch compositions on glass manufacturing differ on each type of glass:

- Type I - Borosilicate Glass
- Type II - Soda Lime Glass

Batch is mainly including 70% of sand together with specific mixtures of soda, ashes, limestone and/or other natural substance that could be magnesium, calcium oxides or sodium sulphates, in order to bestow on glass specific desired properties: color, brilliance, density, among other.

When manufacturing soda lime glass or also known as cullet, recycled glass, is commonly introduced as an additional key ingredient. The amount of cullet used in the batch of glass varies. Cullet melts at a lower temperature which reduces energy consumption and requires fewer raw materials.

Contrarily, borosilicate glass should not be used as recycled component, as due to its heat-resistant properties it would not melt easily, altering viscosity of soda-lime glass batch during re-melt stages.

In summary, all the different raw materials including cullets are stored in a batch. They are then gravity fed into the weighing and mixing area and finally elevated into batch hoppers that supply the glass furnaces.

3.2.1 Methods for producing glass containers

Melting glass constituents at high temperatures (1500ºC) is a common feature on every different glass manufacturing and is by far the most energy-intensive step in the production of glass. Furthermore, other steps and treatment demand relatively high temperatures to eliminate glass structural weaknesses. An overall scheme is showed in Figure 11 [14].

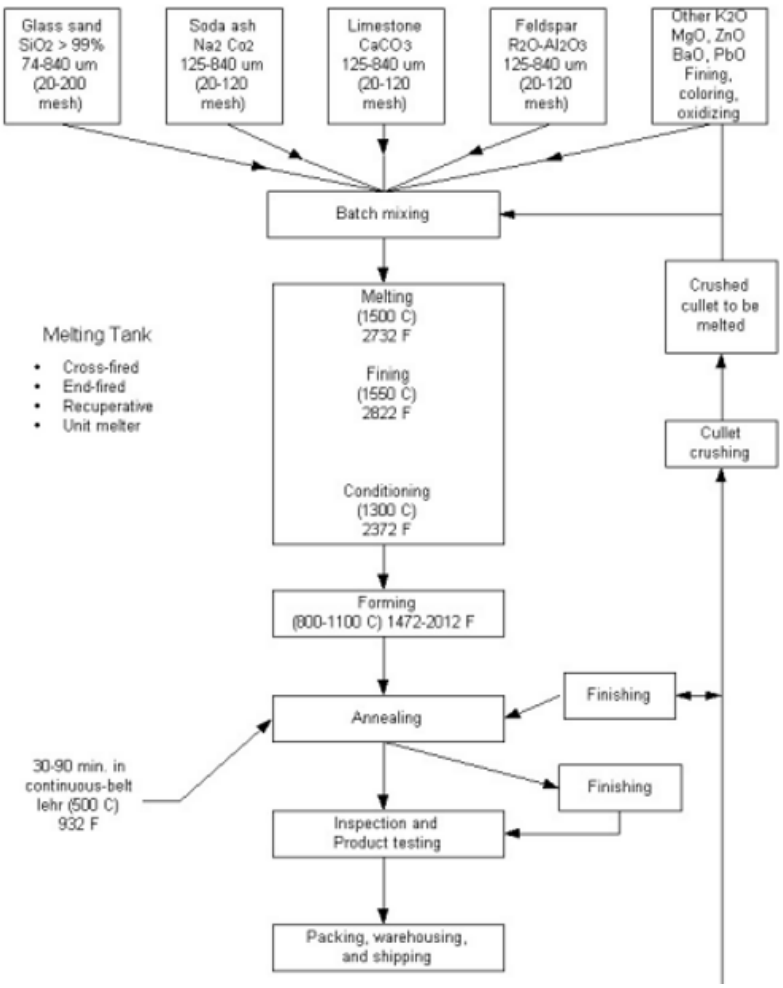


Figure 11: Overview of the Glass Manufacturing Process (Source: Adaptation from Glass Industries of the Future Report, Pellegrino 2002)

Generally, two different methods are extended to give glass different container forms. These methods can be classified as:

- **Blown glass (or molded glass):** gobs of heated glass from the furnace are directed to a molding machine and into the cavities where air is forced in to produce the neck and general container shape. There are two distinct forming processes:

  - **Blow and Blow**: used for narrow containers where compressed air is use (Figure 12):

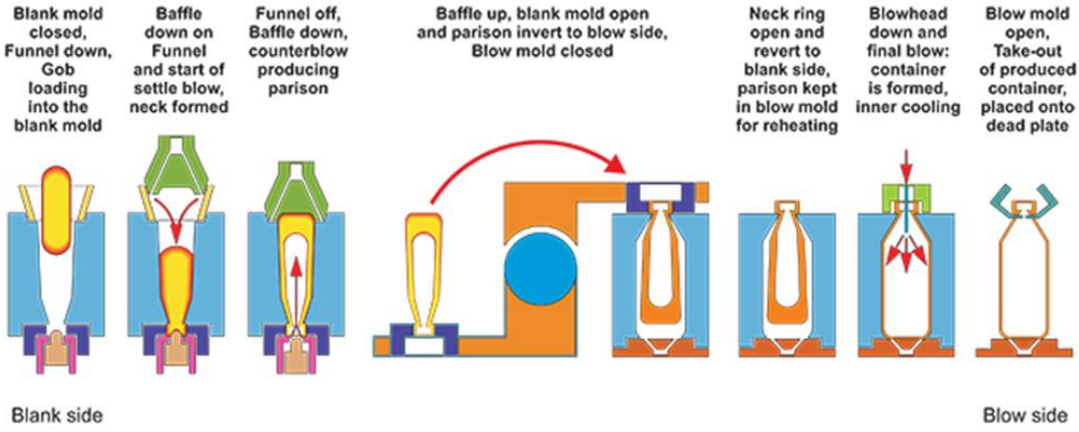


Figure 12: Blow and Blow Process (Source: Qorpak[1])

  - **Press and Blow**: used for large diameter containers, where the container is shaped by pressing the glass against a blank mold with the metal plunger:

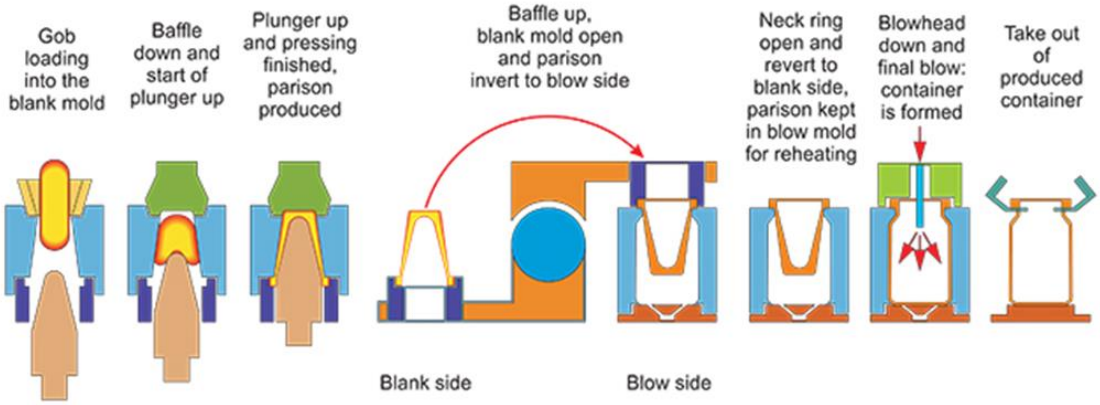


Figure 13: Press and Blow Process (Source: Qorpak)

- **Tubing glass**: continuous draw process over a line of support rollers by drawing machine

[1] https://www.qorpak.com/pages/glassbottlemanufacturingprocess

using either the Danner or Vello processes to achieve desired diameter and thickness

- **Danner Process:** glass flows from a furnace forehearth in the form of a ribbon (Figure 14):

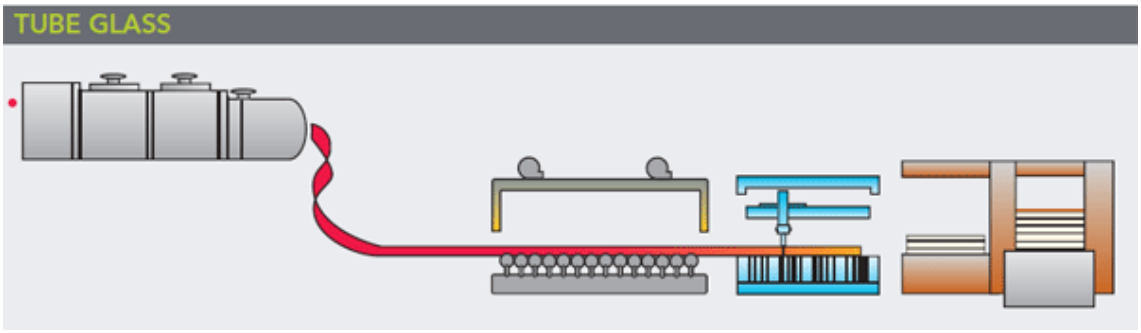


Figure 14: Danner Process (Source: Qorpak)

- **Vello Process**: glass flows from a furnace forehearth into a bowl which is then shaped:

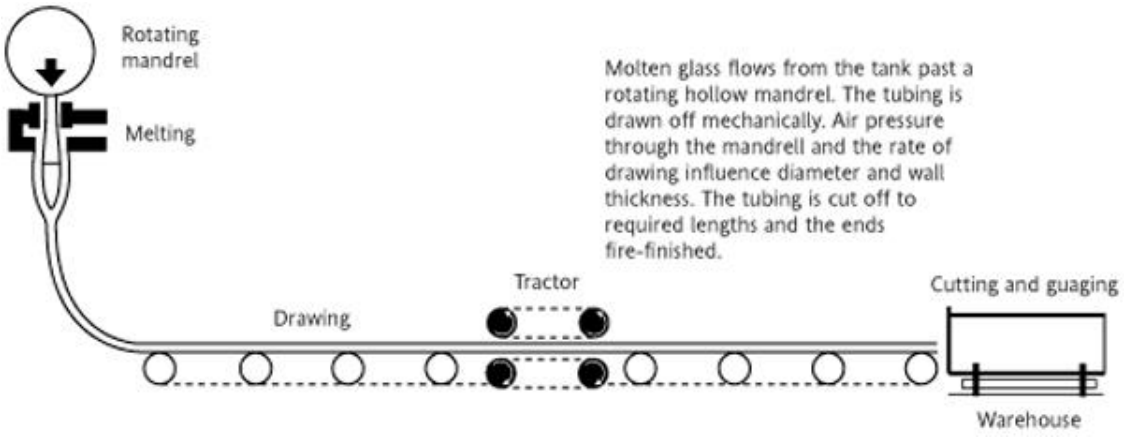


Figure 15: Vello Process (Source: Qorpak)

Further steps are required, implying:

- **Conditioning**: once the blown glass is formed, their temperature is brough near to 900ºC, then reduced gradually below 500ºC. This works to eliminate the stress in the containers, otherwise glass could easily shatter. This process is also complemented with annealing.
- **Surface treatment**: to prevent abrading, which increase the risk of breakage. Some material as polyethylene or tin oxide is used as thin coating sprayed to the surface, avoiding sticking between bottles.
- **Internal treatment**: Usually fluorination for soda-lime glass to prevent from bloom
- **Quality inspections**: measuring bottle weight, dimensions through electronic machines that detect existing faults automatically.

3.3 Energy and GHG emissions

The major energy inputs for glass-container production from raw materials are fossil fuels (mainly natural gas) and electricity. Natural gas is predominantly used to heat melting furnaces and annealing whilst some electric boosting furnace technologies reduce fossil fuel consumption. Additional coal and gas consumptions could be correlated from mining and processing of raw materials.

The energy consumption from melting steps varies depending on multiple factors. However, some data track overall consumed energy in processing glass containers on 11.7 GJ per ton of containers delivered (exception of glass container with no postconsumer recycling. It is remarkable to notice that this data is referenced to 1994. If electricity consumption is converted onto primary energy consumption (11 MJ/kWh), the numbers reach 15 GJ of total primary energy usage per tonne [15].

However, considering a glass sector recycling rate of 100%, natural gas consumption could be reduced to 8.8 GJ, thus not representing enough energy savings on overall process. Additional energy savings could be accomplished by reducing energy on raw materials mining, production, and transportation.

To compare the EU Glass sector with that one in the US, Figure 8 shows a primary energy consumption of 52 PJ for the container glass industry in 2012 (US). In 2021, the environment Protection Agency U.S (EPA) reported data on energy consumption and GHG emissions of the container and flat glass subsectors [8]. Recent data are given in the Figure 16 shown below.

Carbon Dioxide Emissions[2]				
(million metric tons carbon dioxide) (MMmt CO2)	--	12	12	-0.4%

Figure 16A total amount of 140 trillion Btu (equivalent to 147 PJ) of natural gas as primary energy consumption took place in 2020. Such amount was later reduced in 2021 to 138 trillion Btu (145 PJ). When considering the electricity consumption by the glass sector, total primary energy reaches 189 PJ and 186 PJ in 2020 and 2021, respectively.

...	2019	2020	2021	Growth (2020-2050)
Propane (trillion Btu)	--	0.0	0.0	- -
Petroleum and Other Liquids Subtotal (trillion Btu)	--	0.0	0.0	- -
Natural Gas (trillion Btu)	--	140.5	138.0	-0.4%
Steam Coal (trillion Btu)	--	0.0	0.0	- -
Purchased Electricity (trillion Btu)	--	40.0	38.5	0.9%
Total (trillion Btu)	--	180.5	176.5	-0.1%
Carbon Dioxide Emissions[2]				
(million metric tons carbon dioxide) (MMmt CO2)	--	12	12	-0.4%

Figure 16: Flat and container glass primary energy consumptions (Source: EPA).

Between 1960 and 2010, the glass industry decreased its CO_2 emissions by 69% per ton of melted glass. In the EU, that reduction is around 40% (Figure 17). Although several initiatives have been used to decarbonize the container glass industry subsector, it still faces several challenges that hinder an even more pronounced reduction of emissions. Melting and refining require intensive energy and environmental costs. The glass sector is responsible of several combustion by-products emissions such as sulphur oxides (SOx), nitrogen oxides (NOx), and CO_2 as a main contributor to global warming. These emissions are directly related to fossil fuel combustions and depends on which fuel is used, but also indirectly to manufacturing process energy efficiency and the use (or not) of cullet, recycled glass.

The container glass subsector is extended throughout Europe as the most recycled packaging material with the highest collection rate, 78% in EU28 by 2019. Figure 18 illustrates the different consolidation rate of container glass collection for recycling among the different European nations. Future objectives target an increase up to 90% of this rate. Moreover, the majority of the near 20 million tons of container glass are destinated to new bottles and jars production.

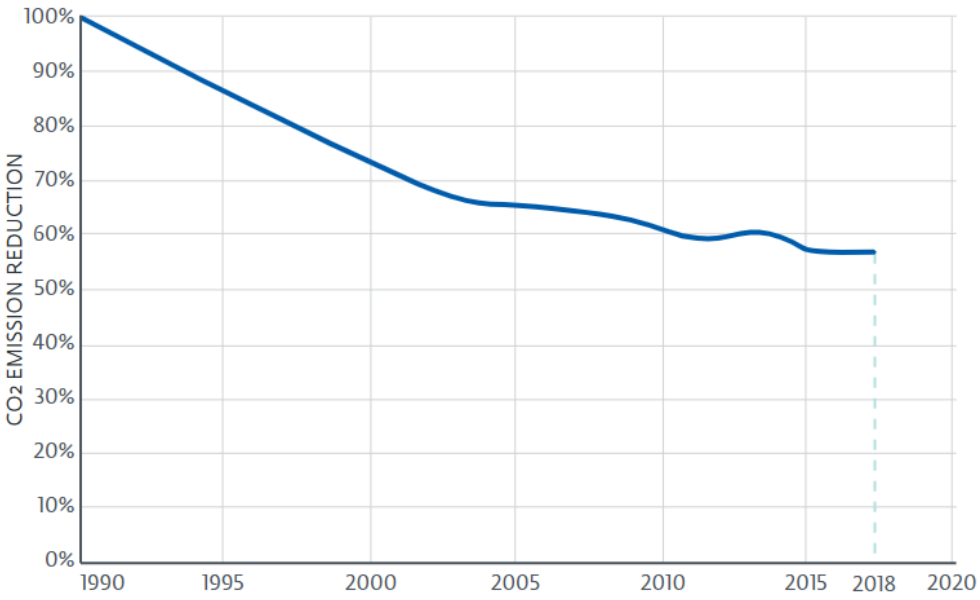


Figure 17: Average CO2 Emissions per Ton of Float Glass Produced in the EU

Regarding Carbon Dioxide equivalent emissions, US share on 2020-2021 shows 13 Mt CO_2:

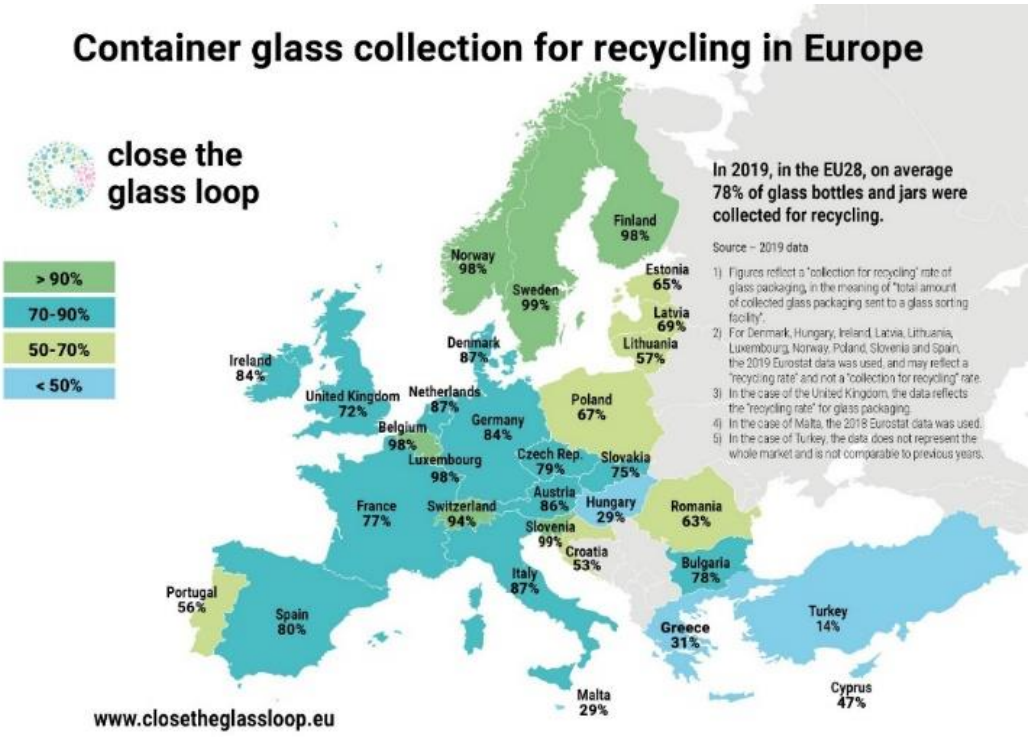


Figure 18: Container glass collection for recycling in Europe (Source: Close the glass loop, 2019)

3.4 Decarbonisation Innovations

Industry is seeking different options either to optimize present manufacturing process or possible new solutions such as carbon storage and utilization. Europe has been investing in both paths through R&D initiatives. Some research is also aiming to shift fuel consumption onto carbon-neutral fuels as biogas, hydrogen or green electricity.

European container glass manufacturers are working on the “furnace of the future,” which will be the world’s first large-scale hybrid electric furnace to run on 80 percent green electricity and is scheduled to be built by 2022 [16].

Other possibilities to minimize emissions in the production process are the acquisition of electric heating technologies. With an insulating layer of batch, or starting material, covering the surface of the glass in a continuous vertical melting process, a well-designed, all-electric melter can have a thermal efficiency of 85 percent, close to twice that of even the most energy efficient fuel-fired furnaces. However, major transformations in manufacturing process, infrastructure, feedstock, and science and technology are still required to cut CO_2 emissions on a much larger scale.

3.4.1 Electrification

Full-electric furnaces would use solely electricity to melt the input materials, reaching such high temperatures due to resistive heating, conducted by electrodes that are inserted in the melt. Electrification applied to furnaces has a higher efficiency than natural gas fueled furnaces. However, electric furnaces are used more often in small-scale applications as its techno-economic viability is still hindered by large scale volumes. For larger scale furnaces, the higher electricity price and lower lifetime largely offsets the efficiency gain, even though electric furnaces are still more efficient. With respect to BAT for furnace electrification, electric furnaces can be around 25% more efficient than conventional furnaces.

Additionally, hybrid furnaces could be also employed. They could complement fossil fuel firing with electric boosting, seeking fossil consumption reduction and increase energy efficiency whilst not renouncing to traditional furnaces.

3.4.2 Increase in the Use of Recycled Glass

One of the most promising technologies to emerge in the glass industry in recent years involves preheating the glass virgin batch materials or cullet before it enters the furnace. Cullet is recycled glass broken into pieces, either from in-house processes or purchased. This is a high-efficiency method involving filtering the pre-glass materials through hot exhaust gases to preheat it prior to melting. Cullet and batch preheating is not yet at a market-ready stage, although government projections have indicated that it could have major implications not only for energy but also for resource savings. Cullet represents up to 20 percent of the materials that go into glass making. Most glass manufacturers use about ten percent of cullet that is recycled during the manufacturing [14]. Manufacturers can also use post-consumer recycled glass, where strict purity is not an issue. Though it is less energy-intensive to process cullet into glass than it is to begin with raw materials, there are economic and energy concerns involved with collecting and transporting recovered glass. Still, in many cases, increasing the percentage of post-consumer glass can have a positive impact on plant energy consumption and overall costs, as well as reduced inputs and emissions.

3.4.3 Comparative assessment of purchased vs. site manufactured gases

Glass manufacturing plants usually purchase gas products such as hydrogen, nitrogen, oxygen, and argon. However, many of these could be on-site-manufactured. With these, an evaluation could be assessed seeking opportunities to develop systems for on-site



production of some of the gases. Moreover, an evaluation of additional gas-use reductions should be an asset.

3.4.4 Biogas

Upgraded biogas (biomethane) has virtually the same composition as regular natural gas (mainly consisting of methane (see Table below). This can be directly injected in the natural gas grid without compromising the quality of the natural gas. Whether or not this will affect the behavior of the melting furnaces is unknown. Since it has virtually the same composition as natural gas, no major adjustments to the furnace are expected to be needed. If a full stream of upgraded biogas is used for both the glass furnace and the curing oven, the only emissions that may be left are *a priori* process emissions. The total emission reduction would be 93% to 94%.

Table 4: Comparison between natural gas, biogas and biomethane [1].

Compound	Natural gas (%)	Biogas (%)	Biomethane (%)
Methane	*87,0-98,0*	*50-75*	*>90*
Ethane	1,5-9,0	N.A.	N.A.
Butane	0,1-1,5	N.A.	N.A.
Pentane	<0,4	N.A.	N.A.
N_2	5,5	0-10	N.A.
CO	0,05-1,0	25-50	N.A.
O_2	<0,1	0-2	N.A.
H_2	N.A.	0-1	<5

3.4.5 Carbon Capture Use & Storage

Carbon capture technologies should be considered to address process emissions in glass manufacturing which cannot be avoided by an energy switch (~25%). Nevertheless, several barriers remain to consider carbon capture as an option. Carbon capture would require creating extensive transport and storage infrastructures to be a large-scale solution by 2050. Considering that the industry is characterized by disseminated units mostly located in brownfields, the CCS/CCU options are also limited by technical constraints (space limitation, presence of acidic compounds, low CO2 concentration), the limited market demand for carbon and societal acceptance.



4. Flat glass

4.1 Introduction

The concept of flat glass lies upstream the glass value chain. All glass goes through a molten (liquid) state and how it is cast (made into its final product) determines its shape, downstream the chain. When molten glass is spread out in sheets on a metal plane, it makes flat glass. The glass is flat like sheets of paper. It is also sometimes called sheet glass and plate glass (see Figure shown below). Hence, it is a term that covers everything from float glass, sheet glass and plate glass, but also processed glass products such as mirrors, windows, bullet-resistant glass or any product initiated from a flat piece of glass [17].

In Table 5: Flat glass chemical composition the composition of flat glass is shown. Due to its composition, flat glass shows a lower performance with respect to physical resistance or chemical durability than e.g container glass [18].

Table 5: Flat glass chemical composition

Oxide Name	Chemical forrmula	Proportion
Silicon dioxide	SiO_2	69 to 74%
Calcium oxide	CaO	5 to 12%
Sodium oxide	Na_2O	12 to 16%
Magnesium oxide	MgO	0 to 6%
Aluminium oxide	Al2O3	0 to 3%

Most of flat glass productions are based on soda-lime silicate glass which shows a better workability.

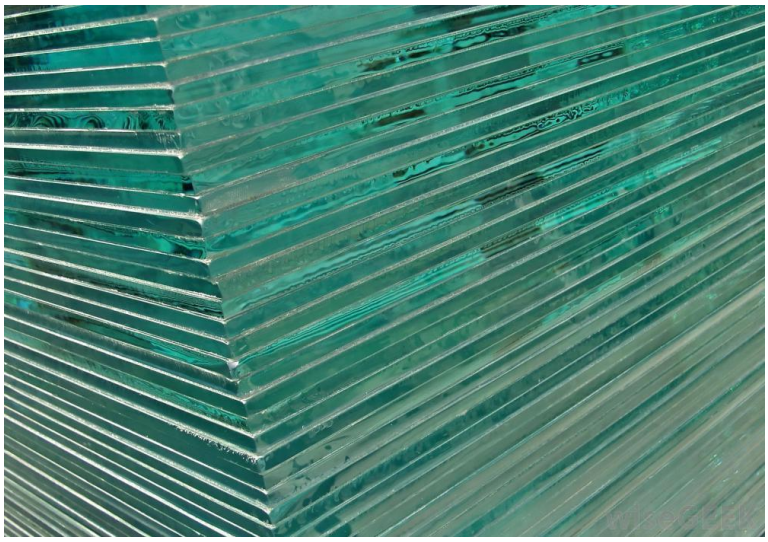


Figure 19: Glass sheets

Flat glass is made by melting sand and other materials into a liquid, spreading the liquid (molten) glass to a desired thickness, and cooling into the final product.

Flat glass market features

Global market situation, in 2020, attains a value of nearly $111 billion, and it is estimated to grow up to $162 billion by 2026 (see Figure 20: shown below). The boost of building and construction, installation of solar panel with rising environmental concern and government initiatives support the growth of the glass sector.

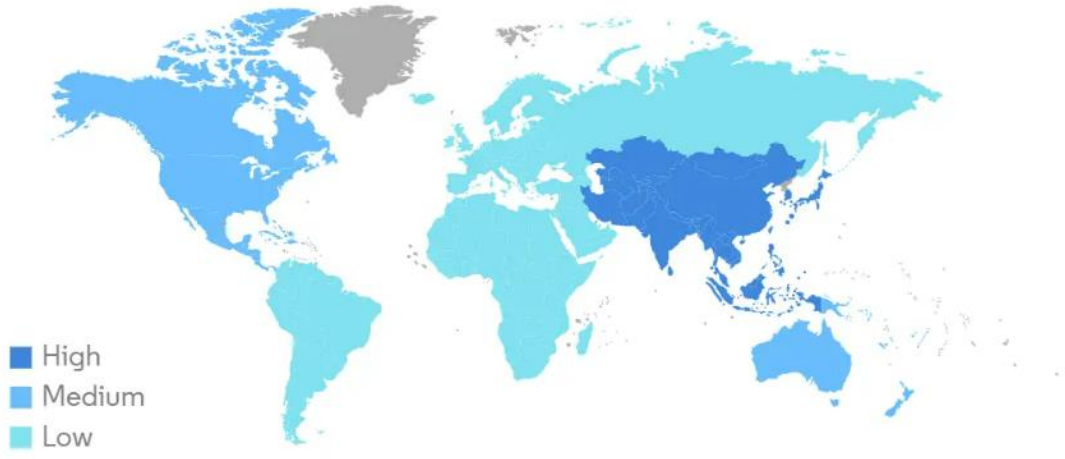


Figure 20: Glass growth rate 2022-2027 (Source: Mordor Intelligence)

China plays the main role as the largest flat glass producer in the world, with more than 50% share of the market in its region. The Chinese flat glass industry has introduced Western production and environmental standards to increase its competitiveness. However, the activity of the construction sector in Asia seems to be decreasing in 2022. Thus, it is expected that the flat glass Chinese manufacturers might deviate from regional trends [19].

Concerning the European market, flat glass is focused on more specific sectors such as construction (building industry accounting more than 80% of the flat glass industry market output), transportation (15% of flat glass is processed into glazing for the automotive industry) and some other sectors, as applications for solar energy devices, appliances, electronics and furniture among other.

The European Union data amounts for up to 10 million tons of flat glass consumed every year among flat glass value chain stakeholders, which are composed of around 60 manufacturing installations in 12 different European countries and over 1000 companies which transform this material into its products. Main manufacturing utilities are in Germany, Poland, France, Italy, Spain and UK (Figure 21) [20]. The European flat glass market is characterized for about a 15 billion$ turnover, and employs nearly 100,000 people.

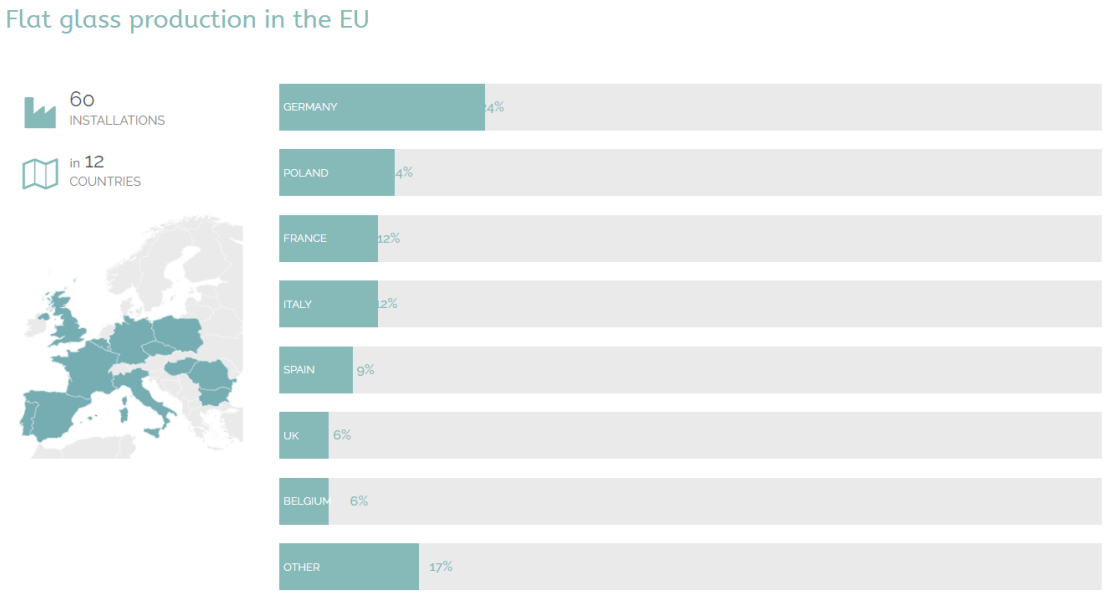


Figure 21: Flat glass production in the EU. (Source: Glass for Europe)

The glazing process consist in a revesting action of surfaces with glass. It represents the main application for flat glass among sectors. The installation of energy performance glazing when windows are replaced or their installation in constructed new buildings are a *sine qua non* strategy for a decarbonized building stock. On average, 48% of the building facade is glass while this can go up to 100% in skyscrapers. Glazing has strengthened its position as an essential construction material for low energy buildings.

Furthermore, glass also constitutes an integral part of vehicles. It contributes to decrease vehicles' weight, thus reducing overall transport emissions. More innovative utilities as solar control glass, minimizes air conditioning needs, hence reducing even more the indirect emissions.

Not only flat glass is contributing to decarbonization strategies through energy saving, but also it is a key material to produce photovoltaic energy cells or acts as direct enabler of the digital transition assembling components of smart devices such as smartphones, tablets, laptops, smart mirrors and other digital displays.

4.2 Production Process

Float glass is made by floating molten glass on a bed of molten tin. The molten glass spreads onto the surface of the metal (generally tin) and produces a high quality, consistently level sheet of glass that is later cut into required sizes. This method gives the glass uniform thickness and a very flat surface (Figure 22).

This technique can continuously produce glass 24/7. It is therefore a river of glass that exits the furnace before being cooled as it progresses along its path of around 300 meters and is then cut into very large sheets.

The float glass production process can be divided into five universal steps:

1. **Batching raw materials and recycled glass (cullet):** it is crucial to determinate batch composition precisely with a high-quality standards of float glass properties.
2. **Melting materials** with temperatures up to 1600ºC, known as the most energy demanding step.
3. **Drawing molten glass onto the tin bath:** the molten glass is then "floated" onto a bath of molten tin at a temperature of about 1000°C. It forms a “ribbon” that is more malleable. By suitably drawing the glass through a complex process involving top roll machines, desired thickness can be achieved. The glass, which is highly viscous, and the tin, which is very fluid, do not mix and the contact surface between these two materials is perfectly flat, giving the term “flat” glass to the final product.
4. **Cooling of the molten glass in the Annealing Lehr:** The mixture at a temperature of 600°C is cooled down sufficiently to pass to an annealing chamber called a “lehr”. The glass is now hard enough to pass over rollers and is annealed, which modifies the internal stresses, enabling it to be cut and worked in a predictable way and ensuring flatness of the glass. As both surfaces are fire finished, they need no grinding or polishing.
5. **Quality checks, automatic cutting, and storage:** after quality checks, flat glass can be now cut into sheets with desired length.



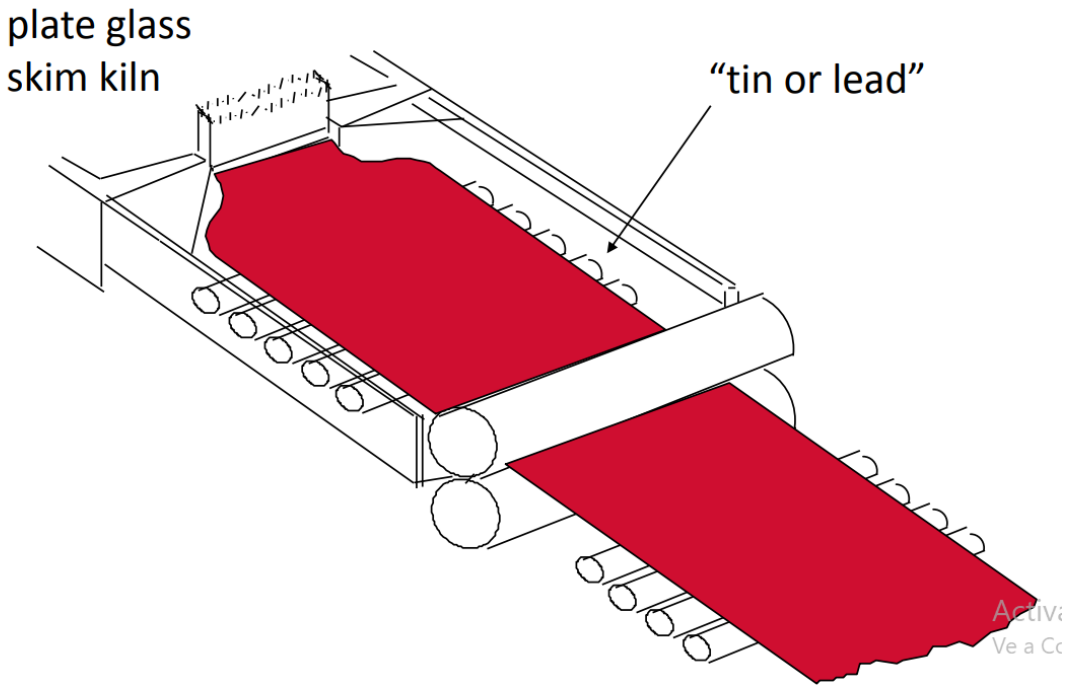


Figure 22: Illustration of continuous float glass, exit to the oven (Source: PPG Flat Glass, 2015)

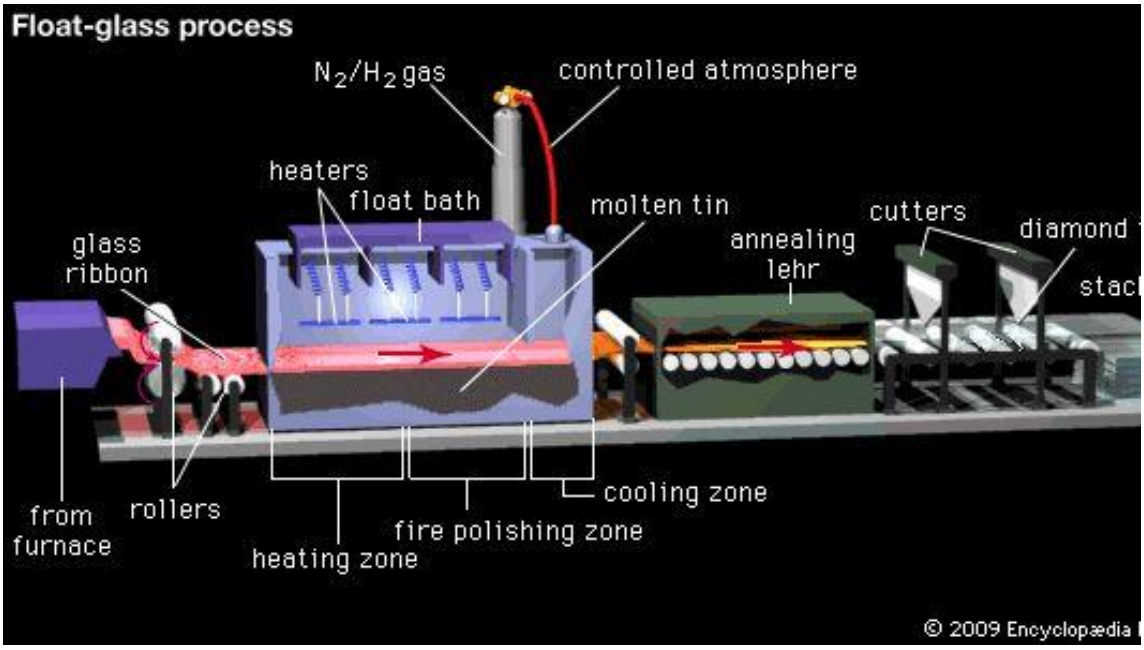


Figure 23: Float glass production process. (Source: Encyclopædia Britannica, Inc)

4.3 Energy and GHG emissions

The flat glass sector total emissions in the EU in 2017 was 5.8 Mt CO2, within EUTL database. Thus, flat glass production represents 0.65% of EU's industrial CO_2 emissions. A common feature among of glass subsectors is their emissions. Approximately, 75% of carbon emissions are originated from natural gas combustion to heat melting furnaces. The remaining 25% may come from CO_2 release of carbonate raw materials, and indirect emissions.

The use of recycled glass or cullet, as raw material is also critical for the industry. This requires less energy to melt and contributes to reducing energy consumption and 'heat-related CO_2 emissions. It also helps reducing 'process emissions' as cullet saves 1.2 times the same quantity of raw materials. Today, 26% of the raw materials input that goes into European flat glass furnaces is cullet.

China is the largest flat glass producer worldwide. The comparison between the two regions, China and the EU, taking into account not only their market size but also the amount of cullet used, produces the following results. China float glass industry emits on average 90% more CO_2 and consumes 32% more energy for the similar production obtained in the EU [21] [22].

Regarding primary energy concerns, an average flat plant of 650 tons per day, may have heat and energy needs near 1.4 PJ, which are mainly fueled by natural gas.

It is reported that the energy intensity of continuous glass furnaces in Europe and the US is between 5 to 8.5 GJ per ton of flat glass, depending on the size and technology of the furnace and the share of cullet used. Moreover, the energy consumption for batch production is higher, typically 12.5 to 30 GJ/ per ton of product. Assuming an average energy use of 7 GJ per ton of product, and natural gas and fuel oil as main energy sources, an emission factor of near 0.5 Mt CO2/ per ton of product can be considered.

Thus, energy used in the production of container and flat glass results in emissions of approximately 40 to 50 Mt CO_2 worldwide (11 to 14 MtC) per year. [23]

4.4 Decarbonization innovations

Around 75% of flat glass furnaces emissions result from the use of fossil fuel to melt raw materials. The switch of this primary energy source has great potential to impact on carbon and GHG emissions. To accomplish this energy switch not only further research in this direction is required but also alternative energy sources needed to be widely available in



sufficient quality and quantity at an economic viable cost. Nowadays, the most promising options considered are biogas, electricity, green hydrogen and biomass [24].

As biogas and electrification have been described in previous sections (see above), the following section will be focused on the use of hydrogen and biomass for the decarbonization of the glass industry.

4.4.1 Switching to carbon neutral fuels: Hydrogen

During the past two years, hydrogen has gained more attention in glass industry. Hydrogen could be applied as combustion fuel instead of natural gas on furnace chambers. However, it should only be considered a decarbonization option when hydrogen has been produced from electrolysis using renewable electricity (green hydrogen) or from natural gas in combination with CCS to mitigate CO_2 emissions (blue hydrogen). The use of hydrogen can have the advantage of cleaner combustion and no CO_2 emissions. For 100% use of hydrogen, oxyfuel burners could be used to combust hydrogen with pure oxygen instead of air, to avoid nitrous oxide (NOx) formation. Main challenges are focused on a higher flame temperature at 2200 °C compared to 1900 °C for natural gas (conventional method). However, how the furnace design needs to be altered is still unknown, especially when looking at the burners, and how the different fuels will affect the melting process and melting efficiency.

Some risks that have not been well-considered yet hinder this transition. The availability of affordable hydrogen produced from renewable electricity (green hydrogen) or hydrogen produced from natural gas in combination with CCS (blue hydrogen), is currently a limiting factor. The current natural gas infrastructure can potentially be refurbished to allow for transport of hydrogen.

As combustion of hydrogen using oxy-fuel hydrogen burners only produces water, just CO_2 emissions from process emissions would remain, resulting in an 95% emission reduction during the melting stage.

4.4.2 Switching to carbon neutral fuels: Biomass

In economic terms, biomass seems a financially much more attractive fuel than electrification or hydrogen combustion. Moreover, it is possible to find already mature technologies in the market in order to use biomass as fuel, which reduce process emissions whilst represent a more economical option than CCS technologies.



A priori, biomass can also directly substitute fossil fuels, but techno-economic studies should be carried out in order to evaluate overall impacts.

However, exist several barriers that limit the reliability of this transition. First, the global supply of sustainable biomass resources is hard to stablish, as it directly overlaps with proper planet boundaries, in global levels. Additionally, re-forestation to generate offsets might be a counter use of biomass rather than the shipping and usage in industrial processes.

Some more advanced technologies are related to biomass in terms of alternative fuels, are pyrolysis bio-oil or gasification methodologies, although readily mature commercial technologies are not yet been established.

5. Special and domestic glass

5.1 Introduction

The special glass subsector relies on high purity glass, usually produced from borosilicate blends. It should be distinguished from conventional soda-lime glass and lead glass. Examples of special glass are lenses, glass products used by the electrical and electronics industries and glass ceramics. The main applications for this kind of glass can be found in the following (non-exhaustive) list:

- **Display and cover glass:** among their end-use applications, one can find screens for laptops, touch panels and other displays. It is a special glass used for thin-film-transistors (TFT), liquid crystal displays (LCD) and OLEDs, including televisions, personal computers and phones. LCDs are conformed by several layers which are a polarizer, color filters and liquid crystal layers, being the last one the more important component.

- **Optical glass:** it is an excellent thermal insulator that helps reducing surface reflection and improves display contrast. This type of glass is considered different from the rest and often more expensive. Its special physical and chemical properties are necessary for its end-use application on lens design, fiber-optic telecommunications systems, mirrors and prisms. Additionally, flint glass and crown glass are widely used in telescopes and medical devices.

- **Technical glass:** the term is referred to lab glass, lighting or surface glass materials



request for exceptional behavior to sudden temperature changes, or thermal shocks, supported with reduced thermal expansion coefficients. For example, thermal expansion coefficient of borosilicate glass, used for domestic cookware, is one-third that of typical soda-lime-silica glass. To achieve these properties, sodium oxide is replaced by boric oxide (B_2O_3) and some of the lime by alumina (Al_2O_3). For surface tableware, lead monoxide (PbO) is used to obtain high refractive properties, hence desired brilliance, and sparkle.

- **Household, domestic glassware or ornamental glass:** it is commonly characterized of colored glasses. Colors are achieved at batching stage, where different metallic oxides are added. Even the same oxide shall produce different colors with different glass mixtures. For example, purple blue of cobalt, chrome green or yellow of chromium, dichroic canary color of uranium, and violet of manganese. Ferrous oxide produces an olive green or a pale blue according to the type of glass. Ferric oxide gives a yellow color but requires an oxidizing agent to prevent reduction to the ferrous state. Lead gives a pale-yellow color. Silver oxide gives a permanent yellow stain [25].

Market features:

Overall global advanced glass has been estimated a worth of $57.66 billion in 2019 (Statista). It is expected that this value will be higher by the next decade due to an increase in consumption from the medical sector, consumer electronics, semiconductors, and other industries. By 2030, the global production is expected to worth around $110 billion [26].

When looking for **specific display glass market**, this is worth around $0.7 billion and is expected to have a CAGR of 6% until 2027. One of the major drivers in this market is the use of LCDs in many devices, such as smartphones, tablets, TVs, and PCs. As LCD has become the main technology used in many devices, especially portable ones, trends in this market show that thickness of display glass substrates tends to reduce.



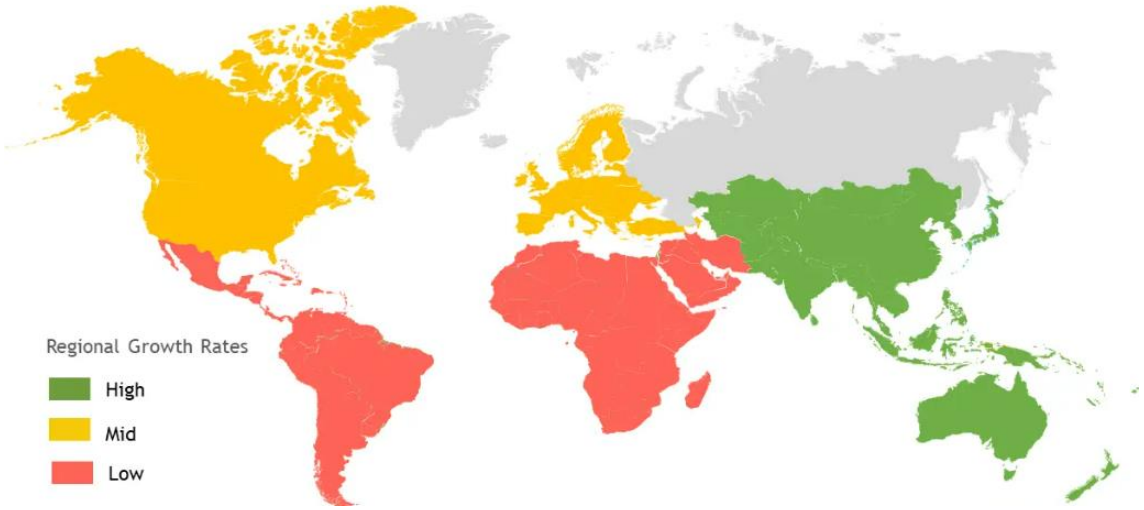


Figure 24: Global display glass market growth rate (Source: Mordor Intelligence)

The market is largely dominated by a few Asian countries such as Korea, Taiwan, Japan and China. These countries form the main manufacturing hub for high quality glass substrates, one of the core elements used in making LCD panels (Figure 24). On the other side, barriers are found in high capital and complex technology requirements.

Just a few companies occupy more than 88% of the global market: Corning, followed by AGC, NEG and Tonghsu, which is the largest producer in China, accounting for over 5% of the global market [27].

The following findings are related to the **optical glass** market. It is expected to reach $2.1 billion by 2026, which means a CAGR of 3.5% during 2021-2026. Asia-Pacific dominates the optical glass market owing to increasing demand from applications such as medical devices, surgical tools, consumer electronics, and semiconductors (Figure 25). The increasing demand for optical eyeglasses and crown glass for consumer electronics are likely to aid in the market growth, which may go forward in the Asian region [28].

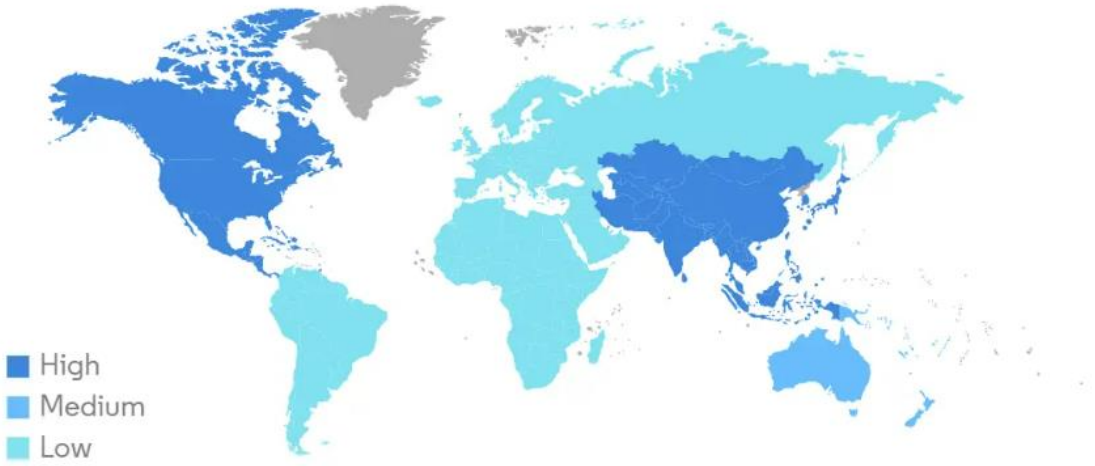


Figure 25: Optical glass market growth rate by 2022-2027 (Source: Mordor intelligence)

Mayor players in optical glass market are PPG Industries Inc, ZEISS International and Nippon Sheet Glass Co. Ltd. The last one occupies the biggest share of Asian market.

In terms of the European market, the combination of special glass subtypes and domestic glassware only shares 1/3 of the European flat glass production. Special glass subsector barely represents 3% of European overall glass industry, where nearly 1 million tons of glass were produced. Moreover, special glass share trends on glass industry have been falling since early 2000s [2] [29].

The special glass capacity of Europe is limited. Most of it is in Germany, which actually plays one of the main roles in Europe overall glass industry. This is also favorable in terms of energy, as electric furnaces are mainly used in domestic and special glass subsectors.

5.2 Energy and GHG emissions

Not enough information has been found reporting data from consumptions and emissions of special glass and glassware industry.

In 2007, for the EU25 the fuel and direct emission for the special glass subsector were 10.6 GJ and 0.72 t CO_2 per ton of product, respectively.

This is available from the EU ETS statistics. When taking into account that 1 million tons of CO_2 are produced for special and domestic glass, it can be calculated that European special glass subsector emitted near 0.72 to 1 Mt of CO_2 whereas primary energy, also mainly supplied by natural gas and electricity, was around 10.6 PJ [30].

5.3 Production process

As any other glass production, batching and melting steps are common. However, there are also some particularities for different specific productions as display or optical glass.

Optical glass must be created with a goal of assuring specific levels of performance from the perspective of how light transmits through it, something not considered with other types of glass. In addition to the optical properties of the glass, designers give attention to the mechanical, chemical, and thermal properties of optical glass. These properties include the material's density, coefficient of thermal expansion, and the maximum operating temperature for the formulation.

To ensure the transparency of glass, the content of colored impurities must be strictly controlled, such as iron, chromium, copper, manganese, cobalt, nickel, etc. It requires accurate weighing and uniform mixing during batching. The main production processes are:

- **Melting:** the batch mixture needs to be stirred. The temperature and stirring are strictly controlled to make the glass liquid highly uniform. High-frequency heating can be used for the production of glass with a large tendency to crystallize, requiring rapid cooling and a specific atmosphere. Since the 1960s, the sector has successively used continuous kiln melting lined with platinum, which has greatly increased the output and quality of optical glass. This is the main trend in the development of optical glass production processes. The molding methods of forming optical glass include classical crucible method, rolling method and pouring method. Currently, leakage molding is used more frequently (using a single crucible or continuous melting out of the liquid), which can directly pull the rod.
- **Annealing.** To eliminate the internal stress of the glass to a greater extent and improve the optical uniformity, it is necessary to formulate a strict annealing system and carry out precision annealing.
- **Indications** measured by inspection are optical constant, optical uniformity, stress birefringence, stripes, bubbles, etc. [30]

From other perspective, display glass can be manufactured using float glass technologies or using Fusion/Overflow technology aiming to produce material as thin as <1mm. Liquid Crystal Display (LCD) has especially critical requirements about product flatness as it can result in distortions of material lens.



The overflow process involves melting glass, and then pouring it into a refractory trough. The glass overflows down both sides of the trough, and then the two flows rejoin together, as the exit from the base of the trough. This process, originally designed for automotive windshields, is used to provide very clean and smooth surfaces on both faces of the glass, thus fusing together (Figure 26).



Figure 26: Overflow melting process for display glass (Source: Corning Glass Technologies)

The width of sheet that can be produced is entirely dependent on the length of the trough and the heating element that can be installed. The longer the element, the wider the sheet, and the more economical the process. For that reason, the demand is focused on longer elements, so that the fusion process can compete with the float process.

5.4 Decarbonization Innovations

5.4.1 Oxy-fuel technologies

By adding oxygen specific points in the melting process, manufacturers can lower the ratio energy/ton product by either increasing output or reducing fuel input. Increased oxygen enables hotter burn temperatures. It has been reported that by increasing the oxygen content of combustion air from, an increase in glass production of 12% percent can be achieved.

Oxygen enriched and oxy-fuel furnaces are used in specialty glass operations to reduce emissions and/or to provide higher production rates for the same size furnace. Although oxyfuel furnaces may produce higher NOx emissions on a concentration basis, they are expected to give very low levels of NOx on a mass basis (kg NOx/ton of glass). Low NOx furnaces, staged firing, and flue gas recirculation are available to reduce NOx emissions in terms of both concentration and mass. These techniques are also available for air-fuel fired furnaces. Levels of NOx can be controlled from 500 to 800 milligrams per cubic meter (mg NOx/m3). Around 20-25% of all glass furnaces used today are oxy-fuel furnaces [31] [32].

5.4.2 Reducing waste glass by improving the precision of lens pressing processes

Spherical lenses are initially pressed from square pieces of glass using metallic molds, and then ground and polished. This pressing process involves countless combinations of glass materials and mold shapes, which are determined by skilled and experienced workers. As a result, the shapes of pressed lenses are slightly inconsistent, so they are made slightly larger to provide extra grinding allowance. However, this also results in a large amount of ground glass being generated as waste in the lens manufacturing process (Figure 27).

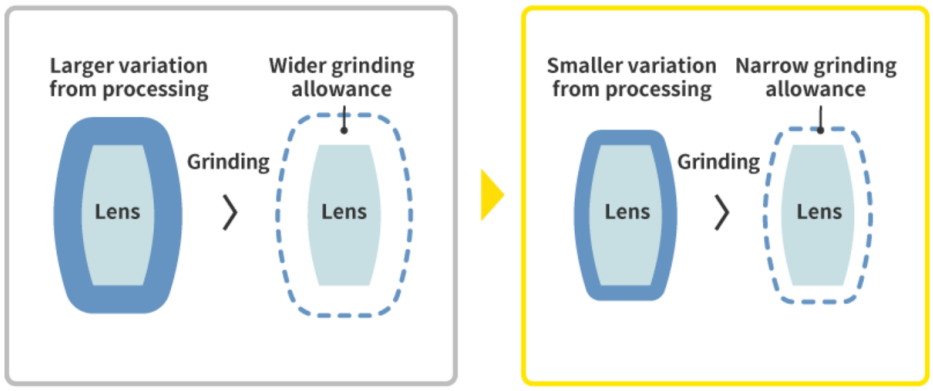


Figure 27: Improvement of precision lens productions process (Source: Nikon)

To solve the problem, **Nikon** looked at each step of its pressing process and improved each one to reduce waste as much as possible. These improvements effectively decreased lens shape variation by about 40% and reduced the amount of glass material per lens by 10%. After extending this initiative to the production of 16 lens products, Nikon succeeded in reducing glass waste by 2.5 tons annually (approximately 36.8 tons of CO_2 equivalent) [33].

5.4.3 Improving optical glass testing efficiency

In the developing of optical glass for cameras or microscopes, small-scale tests must be performed to calibrate manufacturing parameters, and then large-scale tests to verify the feasibility of mass production. During the large-scale tests, uneven temperatures may occur inside the production equipment, requiring the process to be repeated from the small-scale test stage. This not only takes time and energy, but also generates a large amount of glass waste.

In response to this problem, Nikon drew on its expertise in quality engineering to develop a method that enables small-scale test results to be consistently replicated in large-scale tests. Applying this method has brought the time from product development stage to mass production down to less than a year - a third of what it was before. Electricity consumption has also been cut by 170.7 MWh (97.5 tons of CO_2 equivalent) and glass waste reduced by 15.6 tons (228.7 tons of CO_2 equivalent) compared with the situation before innovations. As an added benefit, the new method has greatly reduced the number of product defects during mass production, further reducing glass waste by about 7.0 tons annually (ca. 103 tons of CO_2 equivalent) [33].

6. Glass Fibre

6.1 Introduction

Glass fibers are made from extremely fine fiber of glass, a non-crystalline material with a short-range network structure.

Continuous filament glass fibres (CFCG) are produced in a large variety of forms as roving, mat, chopped strand or textile yarns, which depend on end-use application. Mainly, glass fiber is destinated as a component of resistant composite materials, as reinforcement of a polymer matrix. In fact, these is because glass fibers show amazing mechanical properties which are close to polymers and carbon fibers. Main chemical components of glass fiber are shown in Table 6:

Table 6: Chemical composition by weight of glass fibers (Source: BAT, JRC, 2013)

Component	% by weight
B_2O_3	0 to 10
CaO and MgO	16 to 30
Al_2O_3	12 to 16

SiO_2	52 to 56
Total alkali metal oxides	0 to 2
TiO_2	0 to 1.5
Fe_2O_3	0.05 to 0.8
Fluoride	0 to 1.0

Continuous filament glass fibres can be distinguished from glass-fiber products for insulation which are generally identified as glass wool and are made by a different process.

Figure 28 shows an evolution of the glass fiber market over the last century.

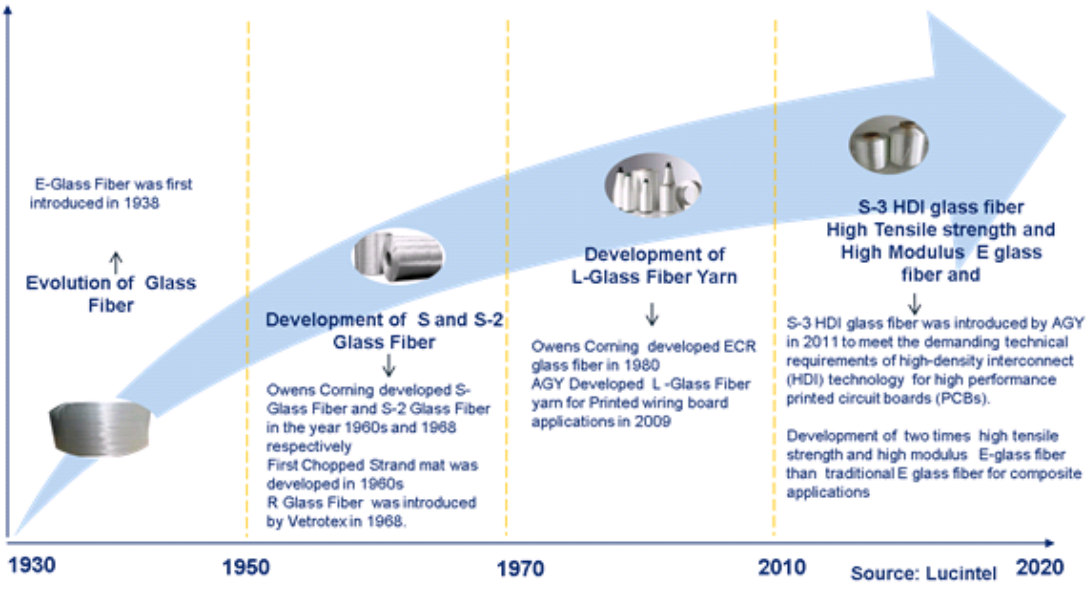


Figure 28: Glass fibre industry evolution (Source: Lucintel)

Glass fiber serves as a great substituent for metal and other resistant materials. It has ended as an indispensable material for construction, transportation, electronics, electrical, chemical or even for aerospace engineering. Nowadays, the world's major glass fiber producers and consumptions are concentrated in a few regions: Europe, Japan, US and China. It is expected that overall global market will register a CAGR over 4% for 2022-2027 (Figure 29).



Figure 29: Glass fiber growth rate 2022-2027 (Source: Mordor Intelligence)

Glass Fiber market Features:

- Glass fiber is used as eco-friendly construction material in the form of glass-fiber reinforced concrete (GRC).

- The GRC can be part of buildings with a solid appearance without causing weight and environmental distresses. Using glass fiber in the cement mix reinforces the material with corrosion-proof sturdy fibers, which make GRC long-lasting for any construction requirement. Owing to the lightweight nature of GRC, the construction of walls, foundations, panels, and cladding is easier and quicker. From the aforementioned factors, the demand for glass fiber in the construction industry is expected to increase in the coming decades.
- Asia's glass fiber industry has been rapidly developed in recent years (especially in China). From 2012 to 2019, its CAGR reached 7% which is higher than the global average. In 2019, the output of glass fiber in mainland China reached 5.27 million tons, accounting for more than half of the total global output. China has become the world's largest glass fiber producer. According to the available statistics, from 2009 to 2019, the global glass fiber output has shown an overall upward trend. In 2018, the global glass fiber output was 7.7 million tons and reached about 8 million tons in 2019, a year-on-year increase of ca. 4% compared to 2018.

Worldwide there are six major manufacturers in the global fiberglass industry: the domestic Jushi Group Co., Ltd., Chongqing International Composite Materials Co., Ltd., Taishan Fiberglass Co., Ltd., and Owens Corning-Vitotex (OCV) in the United States, PPG Industries and Johns Manville (JM).

These 6 companies account for about 73% of the total global glass fiber production capacity. The entire industry is characterized by an oligopoly. Taking into account the production capacity of enterprises in various countries, China accounted for about 60% of global glass fiber production capacity in 2019 [17] [18].

The continuous filament glass fiber market in EU25 represents the smallest glass subsector with about 820.000 tons. The future of the European glass fiber market is promising with opportunities in the transportation, construction, electrical and electronics, pipe and tank, wind energy, and consumer goods industries. The European glass fiber market is expected to reach an estimated $2.1 billion by 2023 with a CAGR of 2.8% until 2023. The major growth driver for this market is the rise in demand for products made of glass composites; these include pipes, tanks, wind blades, bathtubs, and automotive parts.

A graphic summary of glass fiber industry trends is included in Figure 30.

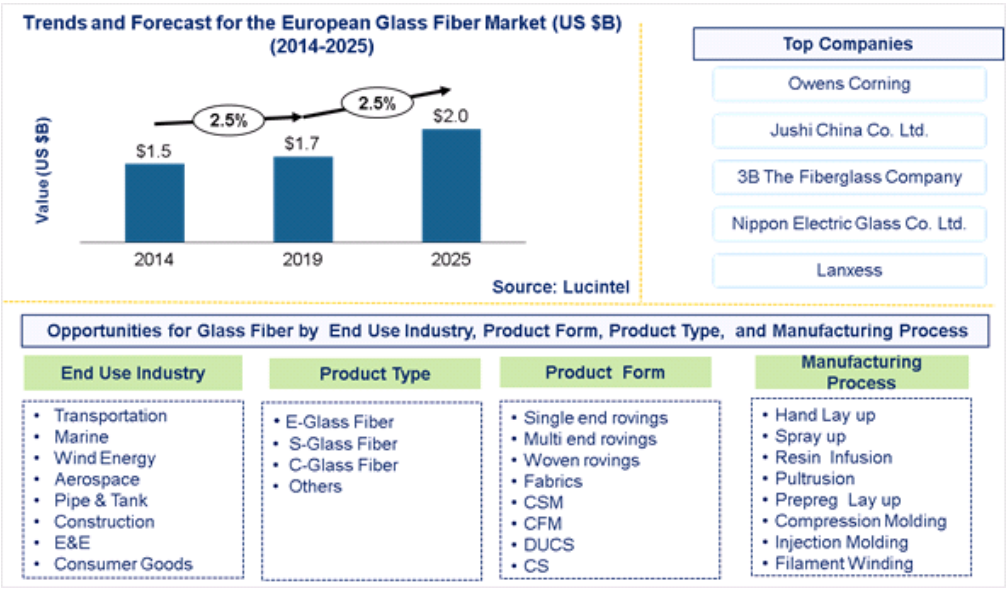


Figure 30: European glass fiber market trends (2014-2025). (Source: Lucintel)

6.2 Production process

Glass fiber manufacturing is the high-temperature conversion of various raw materials (predominantly borosilicates) into a homogeneous melt, followed by the fabrication of this melt into glass fibers. The 2 basic types of glass fiber products, textile, and wool are manufactured by similar processes. A typical diagram of these processes is shown in Figure 31 [19] [20].

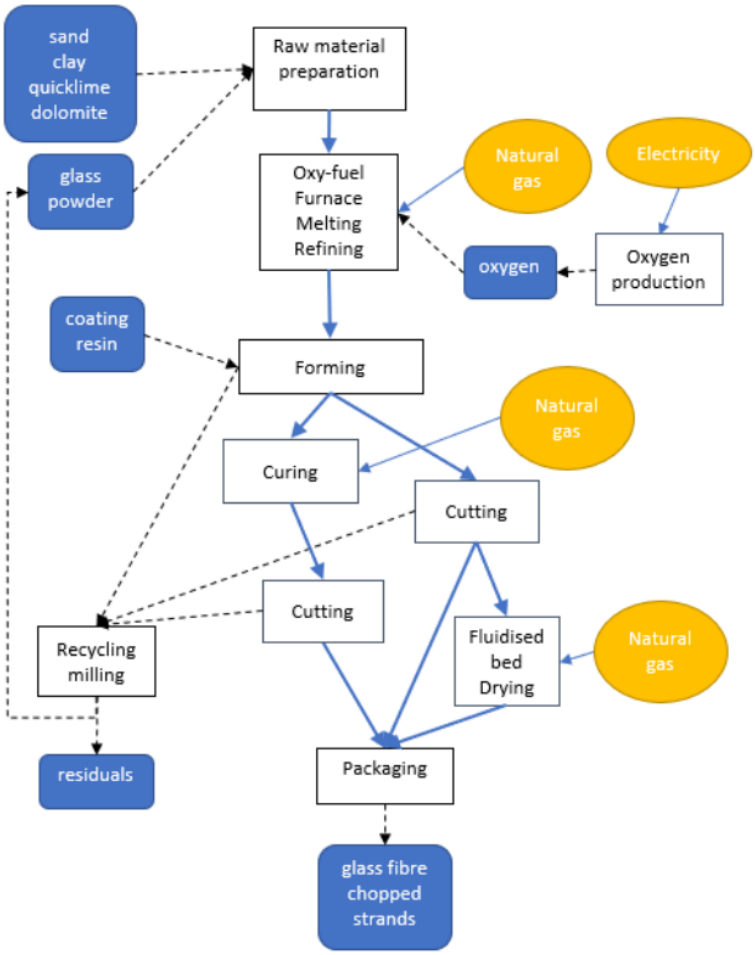


Figure 31: Glass fiber manufacturing processes. (Source: PBL Netherlands Environmental Assessment Agency)

Glass fiber production can be segmented into 3 phases: raw materials handling, glass melting and refining, and wool glass fiber forming and finishing, this last phase being slightly different for textile and wool glass fiber production.

- **Raw Materials Handling**: the primary component of glass fiber is sand, but it also contains several other compounds as feldspar, sodium sulfate, anhydrous borax, boric acid, and many other materials. Conveying to and from storage piles and silos is accomplished by belts, screws, and bucket elevators. From storage, the materials are weighed according to the desired product recipe and then blended well before their introduction into the melting unit. The weighing, mixing, and charging operations may be conducted in either batch or continuous mode.
- **Glass Melting and Refining**. In the glass melting furnace, the raw materials are heated to temperatures ranging from 1500 to 1700°C and are transformed through a sequence of chemical reactions to molten glass. Although there are many furnace designs, furnaces

are generally large, shallow, and well-insulated vessels that are heated from above. In operation, raw materials are introduced continuously on top of a bed of molten glass, where they slowly mix and dissolve. Mixing is carried out by natural convection, gases rising from chemical reactions, and, in some operations, by air injection into the bottom of the bed.

- **Wool Glass Fiber Forming and Finishing:** Wool fiberglass is produced for insulation and is formed into mats that are cut into batts. The insulation is used primarily in the construction industry and is produced to comply with ASTM C167-64, the "Standard Test Method for Thickness and Density of Blanket- or Batt-Type Thermal Insulating Material". Wool fiberglass insulation production lines usually consist of the following processes:
  - preparation of molten glass;
  - formation of fibers into a wool fiberglass mat;
  - curing the binder-coated fiberglass mat;
  - cooling; and
  - backing, cutting, and packaging the insulation.

- **Textile Glass Fiber Forming and Finishing:** Molten glass from either the direct melting furnace or the indirect marble melting furnace which temperature is regulated to a precise viscosity and delivered to forming stations. At the forming stations, the molten glass is forced through heated platinum bushings containing numerous very small openings. The continuous fibers emerging from the openings are drawn over a roller applicator, which applies a coating of a water-soluble sizing and/or coupling agent (Figure 32). The coated fibers are gathered and wound into a spindle. The spindles of glass fibers are next conveyed to a drying oven, where moisture is removed from the sizing and coupling agents. The spindles are then sent to an oven to cure the coatings. For their final form, the fibers are unwound again and divided into the production line of their application (wet or dry chopped strands). The dry chopped strands are dried using a natural gas fired curing oven (at 200 ºC). Finally, the products are packaged and prepared for transport to the customers. The biggest material losses occur during forming (15%) and chopping (5%). Part of the losses can be recycled and used again as input material. The losses from chopping after the curing oven cannot be recycled due to the cured binder attached to the material.



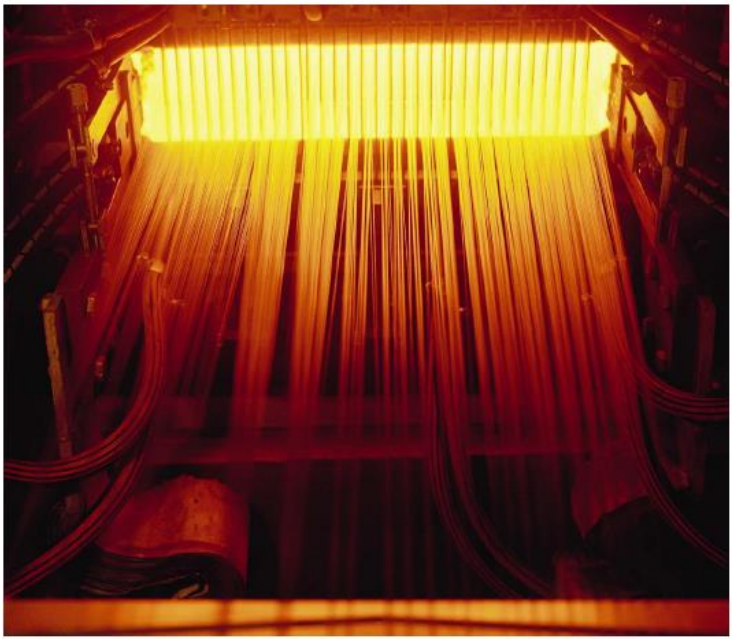


Figure 32: Filaments flowing from the bushing (Saint Gobain Vetrotex, 2019). (Source: PBL Netherlands Environmental Assessment Agency)

6.3 Energy and GHG emissions

The following data are estimated based on the reported EU ETS emissions for 2016 and 2017, which assumed a process emissions rate of 6 to 7%. These are low if they are compared with values estimated from literature of 15%.

Natural gas mainly fueled furnaces lead primary energy consumption near 8.1-9.4 GJ per tonne of glass fiber produced. Additionally, electricity consumption seems to reach near 1/3 of natural gas consumption. Thus, overall primary energy calculated from these data could be 10.8-12.5 GJ per tonne of glass fiber [38][39].

Regarding CO_2 emissions, it was registered that those to relate to combustion processes taking place inside furnaces, heating, melting and forming steps, lead to 0.46-0.53 tons of CO_2 per ton of product. Moreover, those related to other steps involved on process reach 0.03 tons of CO_2 per ton of product. If the 820.000 tons estimated to be produced annually in EU25 are taken into this calculation, carbon emissions could be forecasted to range from 400Mt to 460Mt CO_2..

Nevertheless, different sources were checked to confirm these estimations. A life cycle assessment for CFGF was carried out by PWC in 2016. Results belonging to primary energy and GHC emission are shown in Figure 33 and Figure 34. [40]

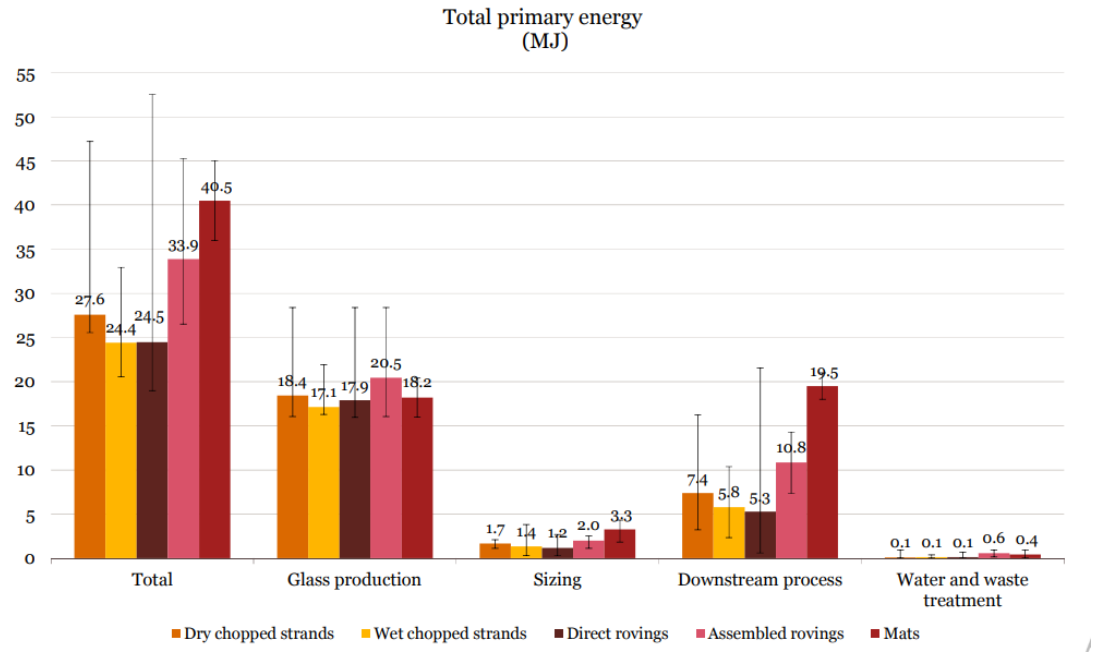


Figure 33: Total primary energy consumption (MJ). (Source: Pwc)

It is remarkable that CFGF are a more complex product that has its origin downstream of glass fiber manufacturing value chain, and thus shall present higher overall numbers.

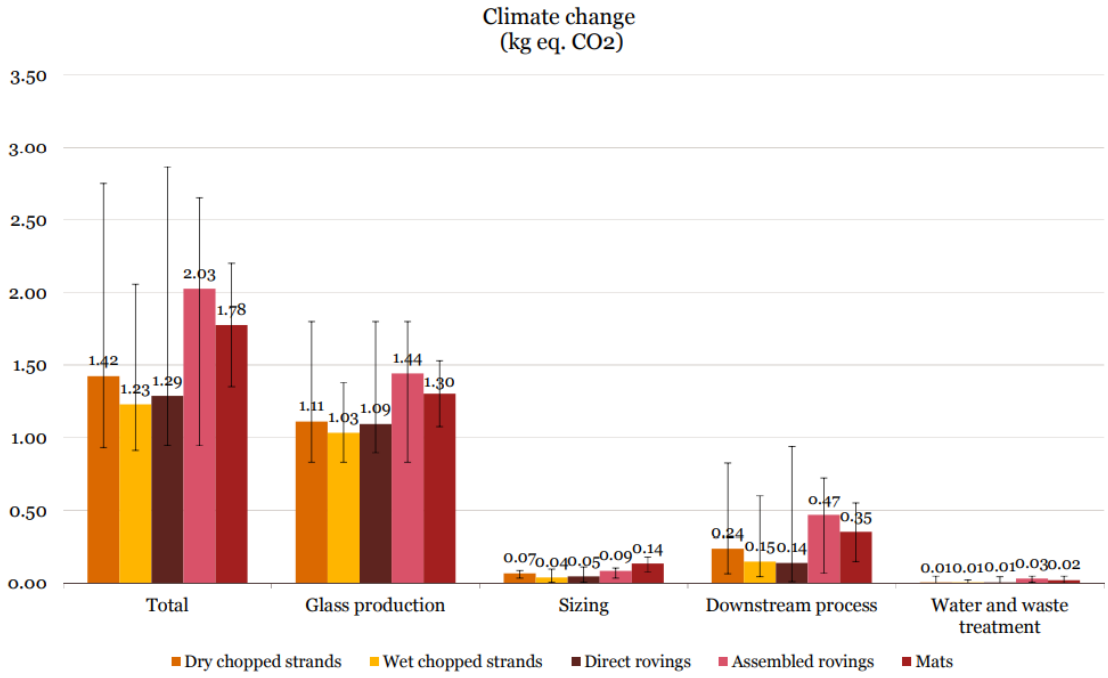


Figure 34: Greenhouse gas emissions (kg eq. CO_2). (Source: PWC)

On average, 27.7 GJ of primary energy are consumed to produce one ton of CFGF product, of which 67% is due to the glass melting process (extraction and transport of raw materials,

furnace). Natural gas represents 55% of this energy consumption. Although primary energy is mostly consumed at the furnace stage, a significant part (27%) of energy is consumed during the downstream process, mainly for drying and by utilities like recycling lines. When looking further at the contributors within the molten glass production stage, process energy consumption represents 56% of primary energy consumed at the glass production stage, and 37% of total primary energy demand.

Primary energy consumed in the furnace is accounted to be 15 GJ (including fossil fuel production and combustion as well as electricity consumption).

Also, the impact of CFGF production on climate change is 1.5 tons eq. CO_2. Direct emissions on site represent 0.57 tonnes eq. CO_2 or 40% of total greenhouse gas emissions. These direct emissions are mainly due to the combustion of natural gas and other fossil fuels and process emissions.

6.4 Decarbonization Innovations

As other glass industry subsectors, the processes that currently have the greatest potential for CO_2 emissions reduction are the melting furnaces and melt feeding channels, which use around 80% of the final energy consumption. The melting furnaces, forming, curing and drying together use more than 95% of the natural gas input. Electrification is an evident alternative that will reduce glass fiber production footprint as to any other glass subsector, hence it will not be further described on this section.

6.4.1 Energy efficiency, waste heat use

Process heat escapes from the furnace through the walls, the melt transport channels or through flue gases. This could represent a potential source of heat supply, and energy efficiency may be increased by using waste heat flows from the production process, to produce e.g., steam. Waste heat in Continuous fiber glass production is often only used for heating buildings as Best Practice Available suggests [22]. Preheating raw materials is limited since they will show unwanted chemical reactions already at low temperatures. Possibly, waste heat can be used in the drying and curing sections, but this would require further studies. A potential application with increasing interest is district heating, enabling Sanitary Hot Water and heating for nearby municipalities.



6.4.2 Recycling

Glass fiber recycling research is ongoing and becoming a more apparent solution to reduce material losses. Several companies aim to introduce in their own processes 100% of their internal glass waste. Recycling of external streams is also an opportunity for increased efficiency and therefore lower emissions. Every 10% increase in recycled glass share in the melt increases the melting efficiency by 2%–3%. Externally recovered continuous glass fiber has limited applicability due to quality constraints. Internal waste usage remains the only option. Incremental production improvements could gradually reduce waste streams. However, it is impossible to completely reduce waste streams, as forming and chopping will always produce some waste. The thin fiber production is sensitive and manufacturing faults are difficult to prevent.

6.4.3 Process cooling system optimization.

The cooling and re-heating steps as fining and conditioning, represent the least energy efficient procedures and also produces a considerable amount of heat waste. For that, cooling water is used for process control and is provided by cooling tower systems. Better controls, variable speed drives, and flow balancing may be implemented so they will enhance cooling system performance resulting in greater overall efficiencies.

7. Conclusions

Today, most of the glass sector emissions are resulting from the use of fossil fuel to melt raw materials. A switch to a carbon neutral source of energy alone is an important reduction potential. Before it materializes, the technology adapted to this new feedstock will need to be found and tested, while alternative energy sources need to be available in sufficient quality and quantity at an economic viable cost. Independently of the glass subsector described in the present report, three renewable technologies could be considered (see below). Unfortunately, none of these technologies meet the required conditions for a full decarbonization of the glass sector. Overcoming technological constraints and ensuring availability of feedstock will be required for an energy switch.

Biomethane. A switch to biomethane is technically possible, particularly with biomethane of similar quality to natural gas. However, leaving aside the cost, quality requirement and distribution challenges, this potential is directly limited by the quantities available. An average float plant of 650 tons a day has energy needs slightly above 1.4 million GJ. It results from the above that, even if the current annual production of biomethane, i.e. 19,352



GWh equivalent to 70 million GJ, was to be entirely directed toward the flat glass sector's plants, this would be insufficient to meet the energy needs of today's 52 EU-based float lines.

Green hydrogen. The injection of more than 20% of hydrogen in the gas grid would require research to adapt the furnace technology. Hydrogen has a high combustion velocity and a non-luminous flame which makes it difficult to monitor. While heat transfer contributes to the efficiency of flat glass making, hydrogen flames provide relatively low radiation heat transfer. In addition, handling and storing hydrogen on site present difficulties due to its explosive properties.

Renewable power. Provided carbon-neutral electricity is available, a major breakthrough in technologies would be needed to make possible full electric melting in glass furnaces. Electric melting is not yet compatible with high temperature glass furnaces with a production above 200 tons a day (i.e. 3 times below an average float glass plant). An additional technical challenge to electric melting is that it is not suitable for high cullet ratios as it is difficult to keep down the superstructure temperatures. Therefore, savings from a switch to carbon neutral electricity could partly be reduced by an increase in process emissions.



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100% Renewable Energies for Energy Intensive Industries

Grant Agreement Nº 952936

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Non-ferrous metals industry

Author: Aimilia Lympeti, Manolis Karampinis

Lead Beneficiary: CERTH

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Abbreviations

Abbreviation	Definition
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CRM	Critical Raw Material
EAF	Electric Arc Furnaces
EII	Energy Intensive Industry
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
PFC	Perfluorocarbon
PPA	Power Purchase Agreements
RE / RES	Renewable Energy / Renewable Energy Sources
RLE	Roasting – Leaching – Electrolysis
SX-EW	Solvent Extraction and Electrowinning
TRL	Technology Readiness Level



1. Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe, focusing on the **non-ferrous metals industrial sector**. The report aims to capture the current status of the non-ferrous metal sector in Europe, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonisation.

Following this introduction, Chapter 2 gives a general overview of the non-ferrous metal sector and its importance for the European and global economy.

Each of the Chapters 3 to 6 focuses on a specific base non-ferrous metal (aluminium, copper, nickel, zinc), while Chapter 7 covers silicon and ferroalloys. The selection of these materials is due to the fact that they are characterized by higher levels of production as well as the highest overall energy consumption. For each metal / metal-alloy, the report provides information on the current usage and importance, main production processes, the energy and GHG emission profile, as well as potential alternatives for cleaner production processes or for mitigating their climate impact.

Finally, Chapter 8 presents the overall challenges and barriers that the non-ferrous industry sector faces and potential measures and solutions for a decarbonised future.

The report is supplemented with four Annexes, which discuss the status of the non-ferrous metals sector in RE4Industry partner countries: Germany, Greece, Netherlands and Spain. Each Annex provides information regarding the main industries which are currently active in the sector, as well as any efforts and commitments undertaken regarding integration of renewable energy sources and decarbonisation in general.



2. The non-ferrous metals sector

2.1 Non-ferrous metal types

Non-ferrous metals are the metals - including alloys – that do not contain iron (ferrite) in appreciable amounts. When the term ferrous metal is used, it typically means that iron is a large percentage of the metal's elemental composition (the second or third largest part of the metal, if it's not the largest). So, non-ferrous metals have small percentage of iron. Non-ferrous alloys generally have iron compositions of less than 1% as measured by weight.

Generally, they are categorized in four main groups:

Base metals are relative common and inexpensive. When exposed to air or moisture, base metals tend to tarnish, oxidize or corrode relatively quickly. They are widely used in numerous applications, such as manufacturing and construction.

Precious metals are rarer and generally less reactive than base metals. Historically, they have been used as currency or for artistic purposes, but currently their value mostly derives from their use as investment commodities or as materials used in specialized industrial applications.

Technology / Specialty metals is a loosely defined group of relative rate metals that are used in high-tech devices, from consumer electronics to medical devices and advanced defence systems.

Rare earth elements / metals include the 15 elements of the lanthanide family, as well yttrium and scandium which are usually found together with the lanthanides and exhibit similar chemical properties. The "rarity" of these metals is not due to their scarcity in Earth's crust but rather due to the lack of several concentrated ores. Rare earth elements have similar chemical properties but each is unique in its electronic / magnetic properties. Rare earth elements fill numerous technological niches and are critical for the development of several high-tech applications or industrial processes.

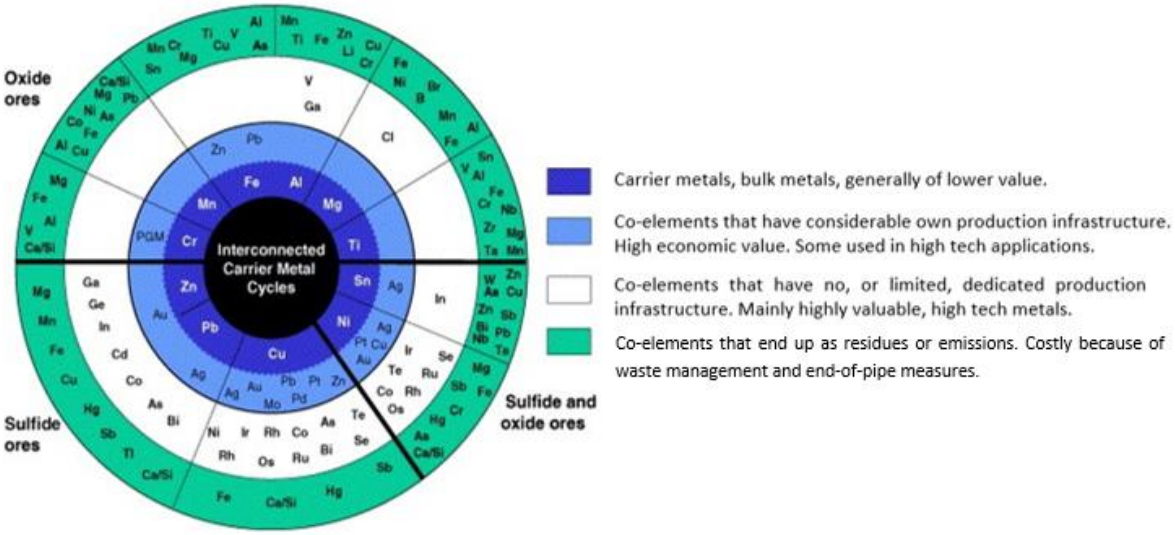
Table 1 – Categories of non-ferrous metals

Base metals	Aluminium (Al), Copper (Cu), Lead (Pb), Nickel (Ni), Tin (Sn), Zinc (Zn)
Precious metals	Gold (Au), Silver (Ag), Platinum (Pt), Palladium (Pd), Ruthenium (Ru), Osmium (Os), Iridium (Ir), Rhodium (Rh)
Technology / Specialty metals	Cobalt (Co), Germanium (Gr), Gallium (Ga), Indium (In), Selenium (Se), Antimony (Sb), Magnesium (Mg), Molybdenum (Mo), Cadmium (Cd), Beryllium (Be), Bismuth (Bi), Chromium (Cr), Niobium (Nb), Vanadium (V), Hafnium (Hf), Lithium (Li), Manganese (Mn), Rhenium (Re), Tantalum (Ta), Tellurium (Te), Titanium (Ti),

	Tungsten (W)
Rare earth elements	Neodymium (Nd), Dysprosium (Dy), Scandium (Sc), Cerium (Ce), Erbium (Er), Europium (Eu), Gadolinium (Gd), Holmium (Ho), Lutetium (Lu), Ytterbium (Yb), Thulium (Tm), Lanthanum (La), Praseodymium (Pr), Samarium (Sm), Terbium (Tb), Yttrium (Y), Promethium (Pm)

Base metals may be carriers of a wide range of other non-ferrous metals; it is often the case that precious and specialty metals are recoverable by-products from the extraction and processing of base metals.

Figure 1 - Non-ferrous metals sector interlinkages, (Source: Reuter et al., 2003)



Silicon is a metalloid. Metalloids are in chemistry chemical elements that has properties intermediate between those of a typical metal and a typical non-metal. Silicon has a significant importance to the economy since it is considered a technology material. It can be considered as a by-product as it is frequently alloyed with non-ferrous metals and its EU production in global share is 9%.

Ferroalloys are alloys of iron with a high proportion of one or more other elements such as manganese (Mn), aluminium (Al), nickel (Ni), or silicon (Si). Ferroalloys are mainly used as master alloys in the iron, foundry and steel industry to improve their tensile strength, wear and corrosion resistance.

The wide use of non-ferrous metal relies on the advantages that make them desirable in many applications. They include high corrosion resistance, great electrical and thermal conductivity, low density (low weight), and non-magnetic properties. Therefore, non-ferrous metals can be considered as building blocks of our society as their value chains connect to vital infrastructure like buildings, transport, electronics, strategic sectors like defence, as well as almost every other economic sector

such as food, jewellery and so on. They are particularly indispensable and irreplaceable in the production of low-carbon technologies.

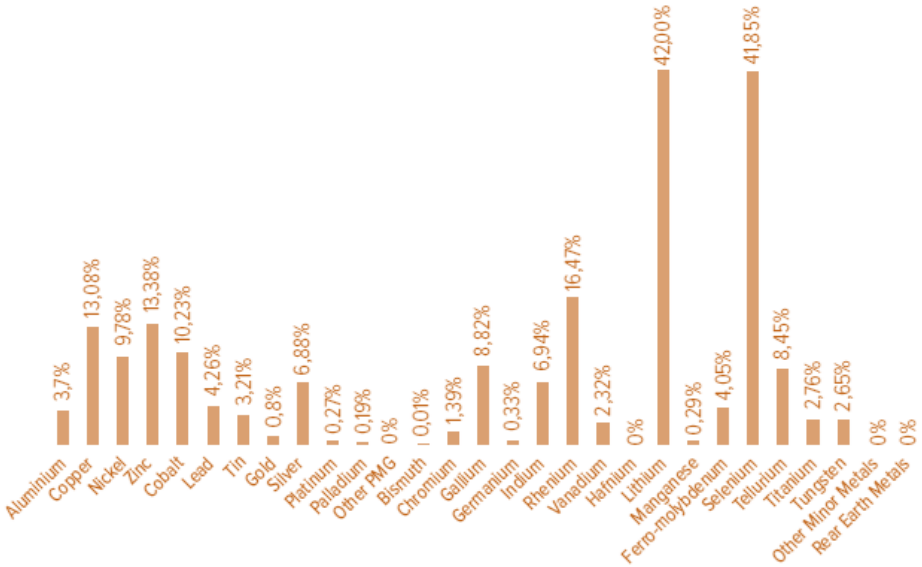
Taking in to account that energy generation, computing, electronic, telecommunications and transport industries depend upon them it is obvious that the non-ferrous metals have an economic and strategic importance for Europe.

2.2 Overview of European non-ferrous metal sector

The non-ferrous metals industry in Europe is worth EUR 120 billion, employing around 500,000 persons directly and more than 2 million people indirectly. The sector consists of 931 facilities, including mining (54 facilities), primary and secondary production of metals (464) and further transformation (413). Metals production is present in most EU member states with a large presence in Italy (179 facilities), Germany (147 facilities), Spain (116 facilities), France (82 facilities), UK (53 facilities), and Poland (51 facilities) [1].

In Europe there is a lack of ore reserves, so the extractive industry (mining) of non-ferrous metal is limited. Consequently, Europe relies heavily on metal ores and concentrates imports from other continents. Taking into account that the World Bank in 2017 projected that 300% more metals will be demanded for the world's wind turbines by 2050, 200% more metals for solar panels and 1000% for batteries [2], it is easy to assume that imports will be increased in the future. At the same time the exports are significantly lower than the import so this import reliance of Europe's for several critical raw materials means that it is entirely dependent on third countries.

Figure 2 - EU primary production of non-ferrous metals as a % of world production (in tonnes), (Source: European Commission[1]*)*



The EU primary production of non-ferrous base metals in 2016 represented 10% of global metals production in 2016 (13 Mt out of 128 Mt). The EU primary base metals production compared to the global one was 6% (6.5 Mt out of 101 Mt), while for secondary production it was 24% (6.5 Mt out of 27 Mt). The EU still has an important share of primary production as a percentage of global production: 4% for aluminium, 13.1% for copper, 9.37% for lead, 9.6% for nickel, and 13.4% for zinc. For cobalt and silicon, the figure stands at 10.23% and 9% respectively. However, for a number of non-ferrous metals, EU production is less than 1% of global production [1].

The interests of the European non-ferrous metals industry are voiced by Eurometaux (www.eurometaux.eu). Currently, the association has 61 members which include non-ferrous metals producers, transformers and recyclers, European metals associations and national metals associations.

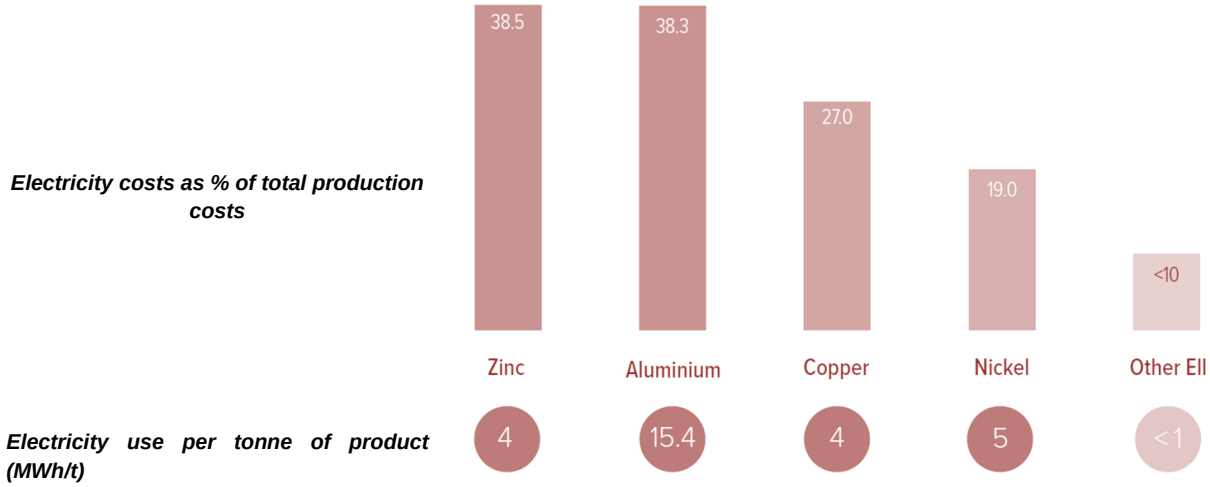
At this time, the biggest non-ferrous metal producers worldwide are China, followed by Russia, USA, Australia, Chile and South Africa. China is the world's largest producer and the largest consumer. This ultimate dominance of China is unambiguous and at the time has a negative impact in the environmental goals as the base metals production in China can be 2.5 to 8 times more carbon-intensive, mainly due to the high use of coal as an energy source [3][4][5].

2.3 Energy consumption and GHG emissions

The non-ferrous metals industry is the most electrified of all energy-intensive industries, with a 58% share of electricity use in its overall energy consumption. As a result, the non-ferrous metals industry is 5 times more sensitive to higher electricity prices than other manufacturing industries [6]. The EU-ETS has a major impact on the sector, as the indirect carbon costs passes from the power producers to the non-ferrous metal producers affecting the competitiveness and economic sustainability of the latter.



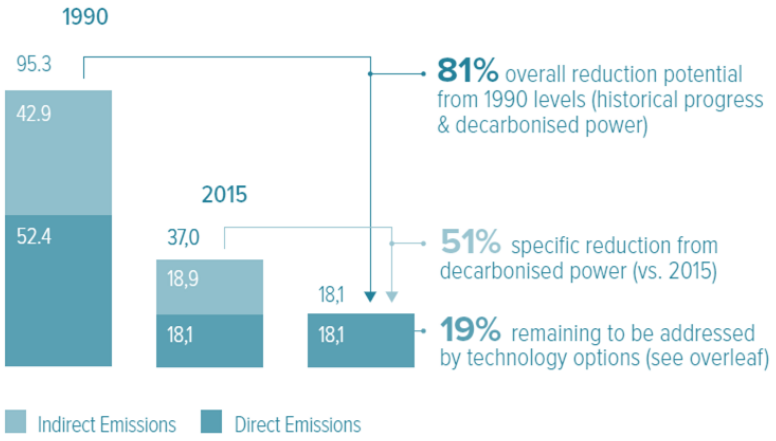
Figure 3 – Importance of electricity in the base non-ferrous metals industry (Source: Eurometaux[1]*)*



On the other hand, the EU non-ferrous metal industry had already achieved to reduce its absolute (direct and indirect) emissions by 61% since 1990, the highest reduction achieved worldwide and retaining the potential of reducing the GHG emissions more than 90% until 2050, a date that marks the EU climate neutrality target.

This mitigation can be achieved only by the decarbonisation of the sector which could lead to a further mitigation of 51% based on 2015 emissions. Therefore, only with the application of decarbonised power there will be a total reduction of 81% since 1990. The remaining emissions could be approached with a wide range of techniques, research, strategy and a supportive policy framework.

Figure 4 - Potential evolution of EU non-ferrous metals industry greenhouse gas emissions from a decarbonised power system, (Source: EEA & Eurostat[1]*)*



2.4 Circularity

A significant characteristic of non-ferrous metals is their ability to be recycled. A strong emphasis on the circularity principle as well as the lack of indigenous resources has made Europe a leader in recycling on non-ferrous metals, with an estimated more than 50% of domestic supplies coming from recycled sources.

The recycling rate in Europe is forecasted to increase even further. Eurometaux estimates that the aluminium scrap treated in the EU will double from 4.5 Mt in 2015 to 9 Mt in 2050; copper scrap will also increase correspondingly from 1.6 to 2.7 Mt [1].

Since the recycling process is less energy-intensive than extraction and primary production, higher recycling levels will have a very positive impact on the overall carbon footprint of the industry. Moreover, along with the recycling of the base metals there is the potential recovery of co-existent elements because all base metals are carriers of a wide range of other base metals, precious metal and specialty metals. This recovery can also take place during the refining as soon as their value surpass their cost and there is financial benefit.



3 Aluminium

3.1 Introduction

Aluminium is an essential material for modern manufacturing. It is a lightweight, high-strength, corrosion-resistant metal with high electrical and thermal conductivity. Tailor-made aluminium alloys can also be created and it is easy to recycle.

More specifically, aluminium is a heat and electricity super-conductor enabling energy-efficient systems, but it is also used for renewable energy applications in charging stations, in wires and cables. In the building sector it is widely used in windows curtain walls and ventilated facades due to its energy performance. Furthermore, aluminium is used in the packaging area because there is little need of material which leads to a lower environmental footprint. Finally, its lightweight properties (1/3 density compared to steel) has shown a reduction of the vehicle emissions during their lifetime.

Figure 5 - Applications of Aluminium, (Source: Kingyear Aluminum Industry)



All the above properties ranked aluminium as the number one most used non-ferrous metal by volume and the second most widely used metal after iron, both in the EU and globally[1].

The European sector consists of more than 600 plants (most of these being small to medium sized enterprises) in 30 countries, and provides indirect employment to more than 1 million persons with an annual turnover of around EUR 40 billion [7]. Primary production of aluminium stands at 2.2 Mt (2016) or 4% of global total primary production. Secondary aluminium production in the EU however

is higher at 3 Mt as compared to 10.1 Mt global secondary production or 29.73%[1]. Apart from Eurometaux, the sector is represented in Europe by "European Aluminium" (https://www.european-aluminium.eu/) which is the voice of the aluminium industry in Europe and currently has 85 member in 600 plants, from 30 European countries.

Figure 6 – Major aluminium producers in the world (Source: European Aluminium)

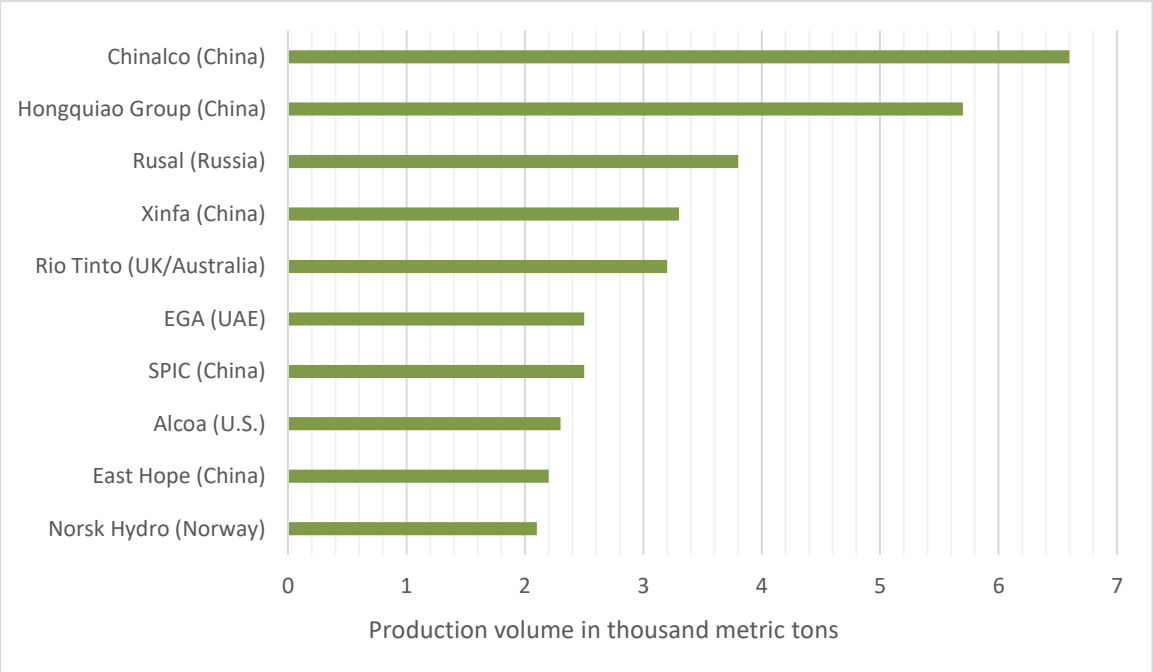
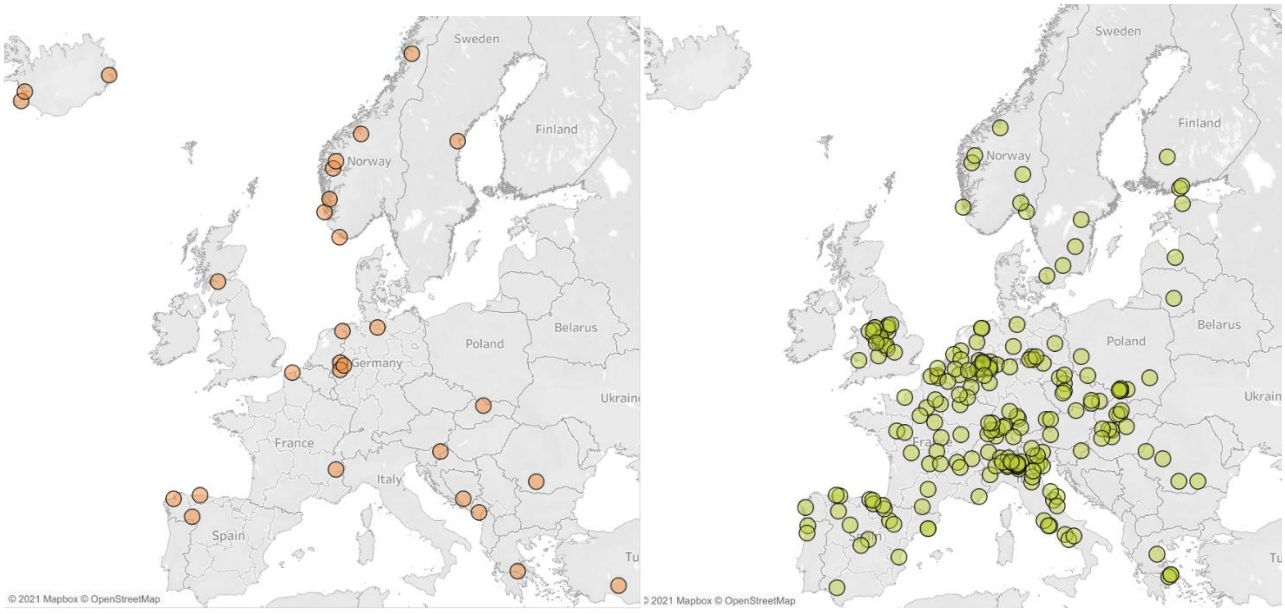


Figure 7 - Primary aluminium production plants (left), recycling aluminium plants (right), (Source: European Aluminium)



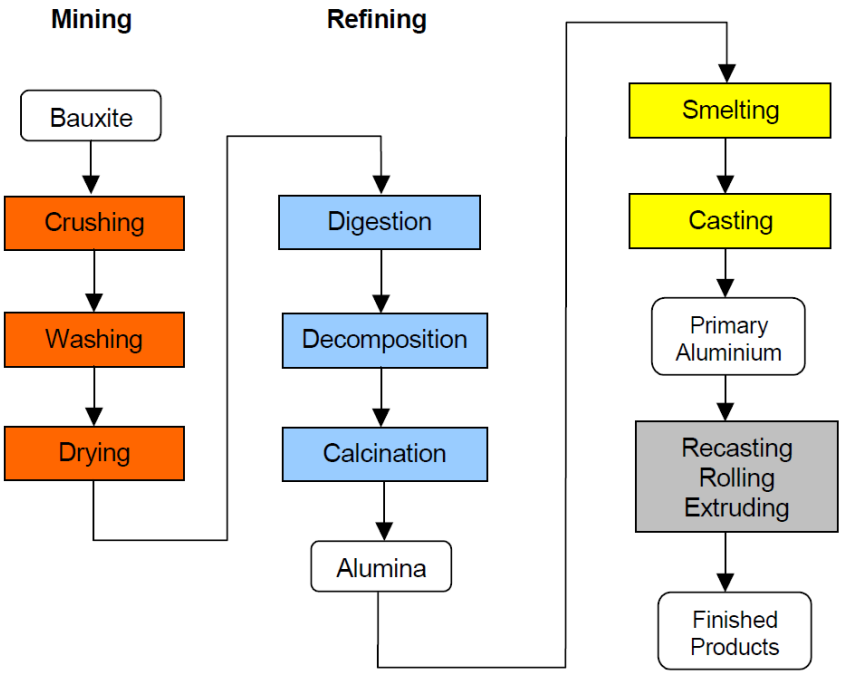
3.2 Production process

Bauxite is the essential raw material for the primary production of aluminium. After the extraction of bauxite ore there are some main processes that are required to produce primary aluminium. These processes are described below:

The first step is the conversion of bauxite into alumina (aluminium oxide). In this refining step (known as Bayer's process), bauxite ore is first crushed and dissolved in hot sodium hydroxide. The iron and other oxides are removed as insoluble 'red mud'. The solution is then precipitated and goes through a calcination process to produce a dry white powder, alumina [8].

Manufacturing of primary aluminium from alumina utilizes a carbon anode in the smelting (Hall-Héroult) process. Most of the carbon of the anodes is consumed during the electrolytic process; therefore, a constant supply is required for the smelting process. Carbon anodes are produced by heating up a mixture of petroleum coke, tar pitch and recycled anode butts (the ends of the consumed anodes that remain after their use).

Figure 8 - Simplified process flow from bauxite to aluminium finished products, (Source: IMIA Conference)

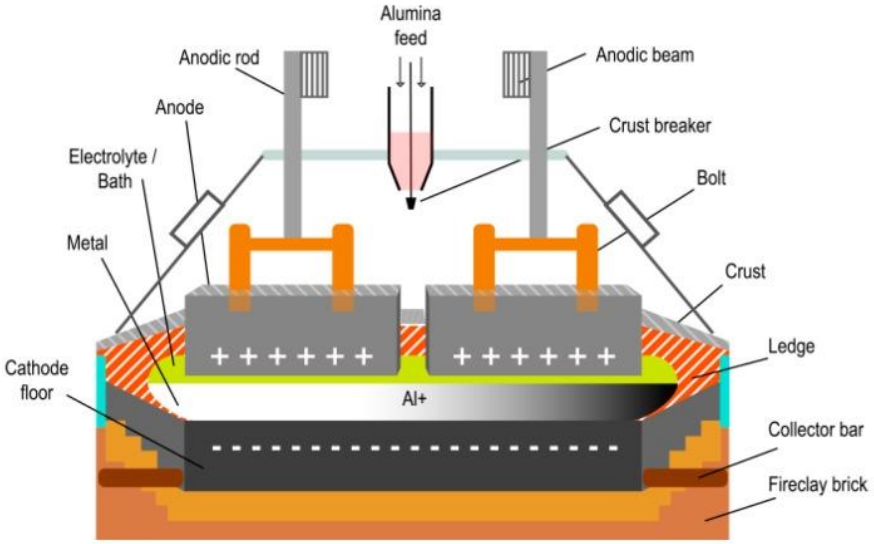


The Hall-Héroult process is the primary process for commercial aluminium production. The process takes place in an electrolytic cell or pot, consisting of two electrodes, anode and cathode. Alumina is dissolved into a cryolite bath and serves as an electrolyte for the process.

High amounts of electrical current are passed through the molten bath and reduces alumina to form

liquid aluminium at the bottom of the cell or pot. Molten aluminium is denser than cryolite and collects on the cell bottom. The metal is generally cast as ingots, which are at least 99% pure with small amounts of iron and silicon being the main impurities [9].

Figure 9 - Primary production of aluminium – electrolysis cell, (Source: Europe PMC)



Typically, a cell has twenty anode blocks, one being replaced each day in a twenty-day cycle (to replace all of the blocks at once would result in too much cooling of the cell), with the block size being designed to give an operating life of 20-21 days [9].

Downstream treatment of aluminium includes rolling mills, extruders and casters.

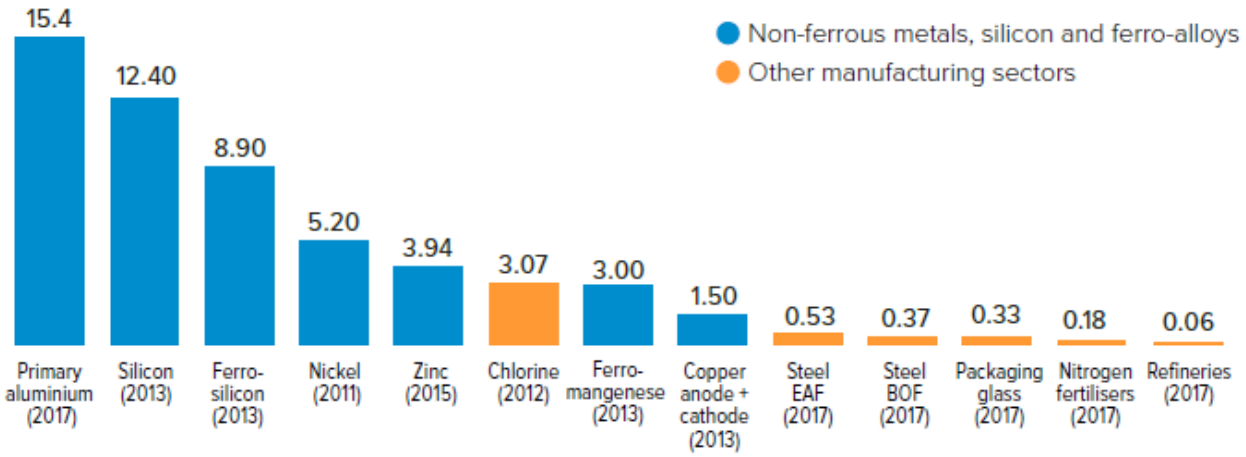
Compared to primary production, the secondary production (e.g. recycling) of aluminium is far less energy intensive due to the lower heating temperature. The process is easier and faster than the primary production as it starts with a pre-treatment of the scrap feedstock according to their quality and characteristics and ends with the melting process in the appropriate furnaces. There is a large variety of furnaces that covers all the needs and depends on the characteristics of the scrap feedstock.

3.3 Energy consumption and GHG emissions

The primary production of aluminium is a highly electro-intensive process which requires 14-16 MWh of electricity per tonne of aluminium produced. The supply of electricity must be steady and uninterrupted. On the other hand, secondary production of aluminium requires only 0.12-0.34 MWh of electricity per tonne [10]. The difference between the amounts of electricity in the primary and secondary production is colossal, a fact that explains the importance of aluminium recycling.

In particular, aluminium has been recycled since the beginning of its industrial production, normally through a re-melting process, as it is less energy-intensive than the process of electrolysis and also more economical, and as a result 75% of all the aluminium ever produced is believed to be still in use. It is noteworthy that recycling 1 kg of aluminium saves up to 8 kg of bauxite ore and 4 kg of other chemical products [10].

Figure 10 - Average electricity use per tonne metal (MWh/t), (Source: Eurometaux[1]*)*



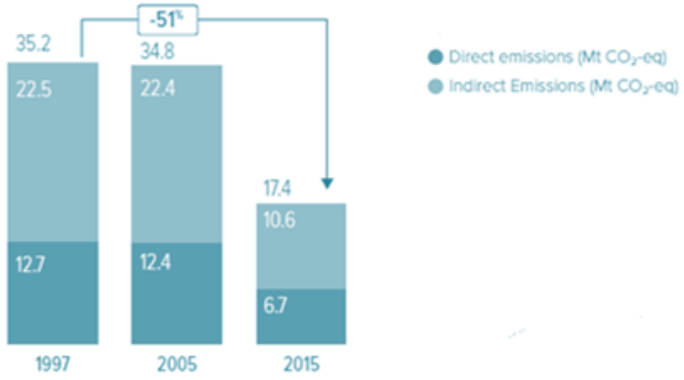
The GHG emissions from aluminium production can be categorized as direct (those corresponding to emissions generated at the production plant itself) and indirect (those corresponding to emissions associated with the production of the electricity used in the process).

Direct GHG emissions from primary aluminium production are not only those generated from the combustion of fuels on the plant, but also process emissions related to the consumption of anodes in the electrolytic cells. Apart from CO_2, various effects in the process of anode consumption lead also to the formation of perfluorocarbons (PFCs), which are very potent greenhouse gases.

Between 1997 and 2015 the total GHG emission from the aluminium production in EU were reduced by 51%, basically due to the reduction of direct emissions by 47%. This reduction came as a result of almost full elimination of PFCs emissions, from 22.8 to 0.4 Mt or down by 98% (1990-2015), due to better process management and flue gas treatment. At the same time emissions from anode consumption decreased 19% between 1997 and 2015 [11].

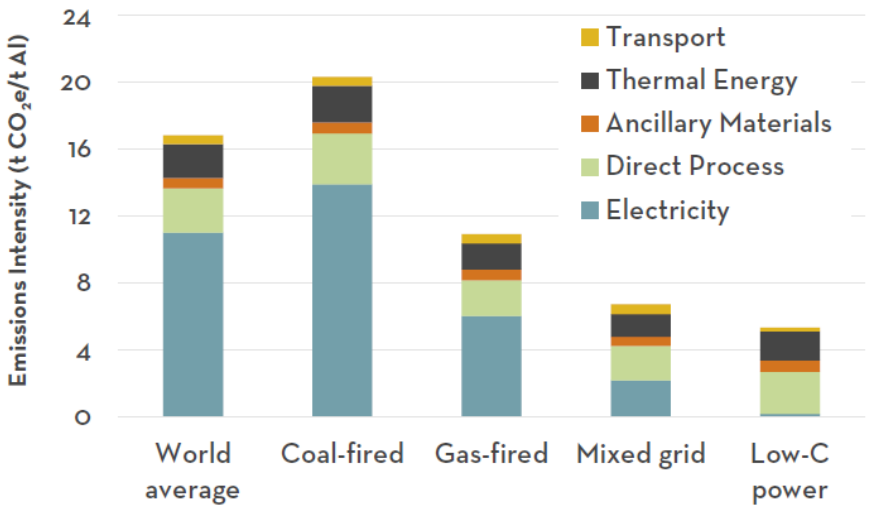
Figure 11 Evolution of GHG emissions from EU28+EFTA aluminium production

(Mt CO_2-eq), (Source: Eurometaux[1]*)*



Finally, indirect emissions fell 53% (1997-2015) due to this decline in production capacity, efficiency improvements and the decarbonisation of the EU power grid. In particular, during 1997-2005 the levels of indirect emissions seem to be stable, however, during this period the production increased 23% and simultaneously the indirect emissions per tonne decreased almost 30%. This explains the stability on emissions levels [3]. On the other hand, between 2005 to 2015 the level of indirect emissions decreased mainly due to the economic crisis but also due to improvements in overall process efficiency. As concerns the economic crisis, the primary capacity in the EU was 35% lower in 2007 comparing to 2006. This fact, depressed global aluminium prices and led to the replacement of EU's production with imports from international competitors with lower production costs and the augmentation of secondary production.

Figure 12 - World average 2018 & typical power mix cradle-to-gate emissions intensity of primary aluminium production [12]



3.4 Energy efficiency and decarbonisation innovations

Primary aluminium production has seen large efficiency gains since it was first introduced. However, there are still technology improvements that can be adopted. The description of some prospective technologies and pilot applications follows.

3.4.1 Wettable cathodes

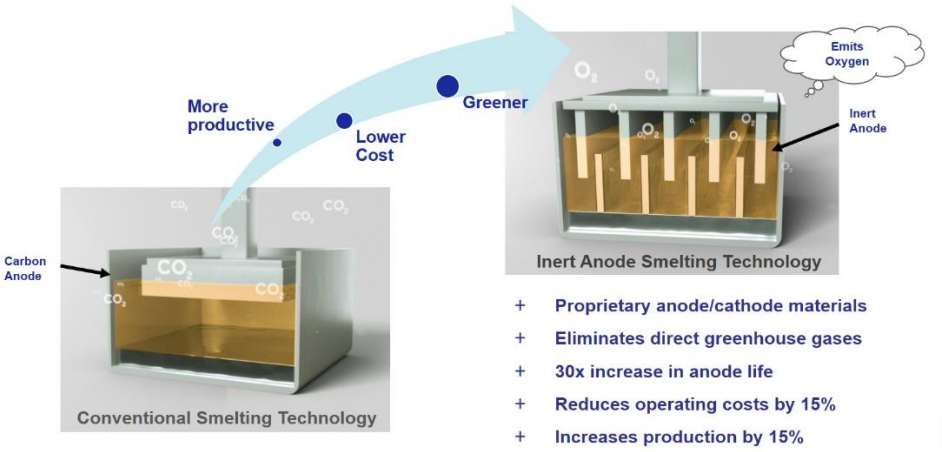
The development of new cathode materials or coatings for existing cathode materials is expected to lead to inert cathodes that are wettable to the molten aluminium pad. This will allow for the reduction of the anode-cathode distance, reducing the voltage drop and helping achieve better energy. The potential energy savings are estimated at up to 15-20 % [13]. Moreover, the use of wettable cathodes is expected to prolong the life of cells and reduce the amount of toxic waste.

3.4.2 Inert anodes

Inert anode technology represents one of the potential future options for the industry. With this development, a completely new electrolytic cell without consumable anodes will be constructed, in which oxygen would be produced at the anode instead of carbon dioxide. Inert anodes would replace the energy-intensive production of carbon anodes. Through their application, it is expected that a substantial energy efficiency will be achieved, coupled with the elimination of the production of (direct) CO_2 emissions due to the consumption of the anode during the aluminium production process. Some other benefits that come along with the inert anodes use is the overall lower capital cost (reduction estimated in the range of 10-30%), the elimination of PFC emissions and the oxygen as possible by-product. Finally, they improve efficiency of the plant because the regularly replacement of the anodes is not required [13]. An additional improvement to the inert anodes' technology could be the creation of multipolar cells, allowing multiple anode-cathode pairs in same cell (compared to only one horizontal cathode now). This implementation can optimize the overall process. This process is not applied to the current Hall–Héroult process, the industrial smelting process of the aluminium.



Figure 13 - Conventional VS Inert anode smelting technology, (Source: European Aluminium)



Finally, the physical design of anodes can be also altered to improve energy efficiency of the Hall-Héroult cells. For instance, sloped and perforated anodes make electrolysis more efficient by allowing better circulation within the electrolyte bath, while vertical electrode cells save energy by reducing heat loss and improving electrical conductivity [14]. However, this new design requires a different type of cathode.

Currently, the frontrunner in developing inert anodes-based aluminium production is ELYSIS (www.elysis.com) a partnership of two major aluminium producers - Alcoa and Rio Tinto. The ELYSIS™ technology promises to eliminate all direct GHG emissions from the aluminium smelting process, while producing oxygen as its by-product. ELYSIS has received investment support from Apple and the Canadian Government with the Quebec Government, through participation of Investissement Quebec.

The technology was successfully demonstrated at the Alcoa Technical Center, near Pittsburgh in the United States, since 2009. In the second half of 2020, Elysis opened a research and development center in Saguenay, Quebec, Canada to further scale-up the process. This research centre is housing the next generation cells with the objective to demonstrate the technology at commercial scale. The goal is to bring the technology to commercial size by 2024 [15].

3.4.3 Lower electrolysis temperature

In current practice, electrolysis is performed at temperatures of around 950 ^{o}C, far above the melting point of aluminium (680 ^{o}C). Theoretically, a reduction of temperature to around melting point while maintaining stable operation could decrease electricity use by 1-1.5 MWh/t although in reality savings are likely to be around 0.7 MWh/t (5%), since with current practice, energy from the superheated metal is generally used to re-melt pre-loaded scrap in the casting house, benefitting from its “free” energy [16]. This technique is available on the market, but to date no smelters use it.

3.4.4 Application of a dynamic AC magnetic field

The application of a dynamic AC magnetic field in electrolysis cells can significantly suppresses ripples in the molten aluminium, enabling smaller electrode separation and therefore lower electricity use. The energy savings associated with this technique are estimated to be between 5-20%. However, this option will be unnecessary if drained, wettable cathodes are successfully implemented [13].

3.4.5 High temperature carbothermic reduction of alumina

The carbo-thermic reduction of alumina has been proposed as an alternative to electrolysis. In this process, alumina reacts with carbon at high temperatures (> 2,000 ˚C) to form aluminium and CO. It would be 20-30% more efficient compared to electrolysis-based aluminium production and have lower (50%) capital costs. The technology has been tested up to pilot scale by Alcoa and Elkem, but further development has stalled [16],[17].

3.4.6 Chloride process

The chloride process developed by Alcoa between 1960-1980, based on the chlorination of refined aluminium oxide, does take place at such lower temperatures. In practice, the chloride process has not been able to compete with the Hall-Héroult process, and little information is available on industrial experience with the method. The chloride process is adversely affected by raw materials impurities, a number of unfortunate side reactions can occur, and gaseous chlorine compounds are generally toxic [18].

3.4.7 Kaolin as raw material in the aluminium production

The chlorination and electrolytic reduction of kaolin which is an alumina-silicate clay, could replace the current Bayer (alumina production) and Hall-Héroult processes. The overall process would be 12- 46% more efficient and would use smaller cells with the ability to retain temperature and would allow aluminium producers to take better advantage of electricity demand response systems[13].The process is still at the early development stages.

3.4.8 Carbon Capture Storage (CCS)

In primary aluminium production can also be applied absorption-based CCS. Because the CO_2 concentration in off-gases from aluminium electrolysis is dilute (4%), costs for capturing are estimated to be around EUR 100/t CO_2 (including additional energy use). However, if inert anodes become available, CCS in primary aluminium production would be unnecessary due to low operational costs of inert anodes [18].



3.4.9 Karmøy Technology Plant

During the last decade, researchers in Norsk Hydro's (www.hydro.com/en) technology centres in Norway have developed a new generation of electrolysis technology. This pilot is taking place in Karmøy plant and aims to reduce both industry energy consumption and emissions and it is now being tested in a full-scale production plant. The pilot was designed with an annual production capacity of approximately 75,000 tonnes. It consists of 48 cells running on the HAL4e technology (12.3 kWh/kg) and 12 cells using the HAL4e Ultra technology (11.5-11.8 kWh/kg).

The new electrolytic cells are 50 % larger and will produce 50 % more metal per cell, using less energy per kilo of aluminium produced. Total costs are estimated at €442 million, consisting of net project costs of €277 million and around €164 million in support from Norwegian government enterprise Enova.

The pilot consists of physical technology elements and an improved process control system. Several of these elements are capable of being tailored for, and used in, Norsk Hydro's existing aluminium plants. This makes the technology an advance not only for Karmøy but for all primary aluminium plants.

This pilot will be reducing direct CO_2 emissions to 1.40-1.45kg CO_2 equivalents per kg aluminium, 0.8 kg below the current world average.

This Hydro-developed technology will use 15 percent less energy for aluminium production than the global average, providing the lowest CO_2 footprint in the world [19].



4 Copper

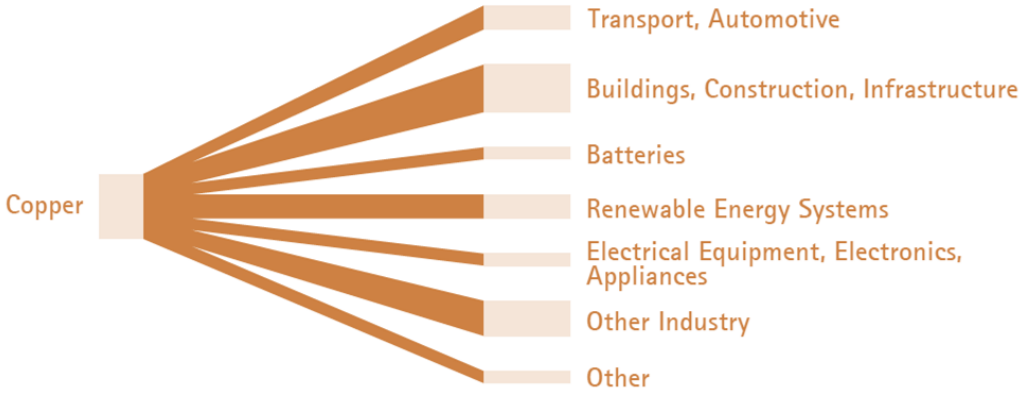
4.1 Introduction

Copper is the second largest non-ferrous, base metal sector in the EU after aluminium with around 500 companies in three sectors (mining, production and semi-fabrication) and an estimated turnover of about EUR 45 billion while employing around 50,000 people [20]. In 2016, primary copper production in the EU stood at 2.3 Mt or 13.1% of global total primary production.

Secondary copper production in the EU, like aluminium, is significantly high, almost 50%, since copper is a permanent material and 100% recyclable. Copper can be recycled repeatedly without any loss of performance, and recycling requires up to 85% less energy than primary production. Globally, this saves 40 million tonnes of CO_2 annually. In 2015, secondary copper production in the EU was almost a quarter of global figures: 1.7 Mt as compared to 7.38 Mt [13]; this figure is projected to increase significantly by 2050 and it is estimated to reach 2.7 Mt.

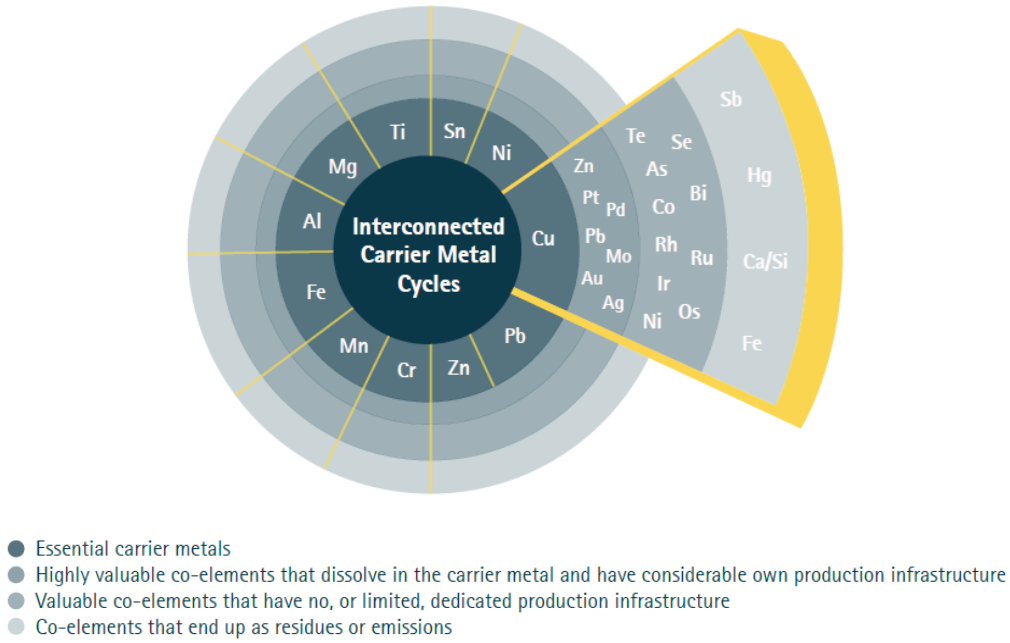
Copper and copper alloys are widely-used in diverse applications from electrical generation and delivery to art and architecture. Moreover, copper will be a crucial metal for the energy transition. Renewable energy systems use up to 12 times more copper than conventional power generation systems.

Figure 14 - Applications of Copper, (Source: European Copper Institute)



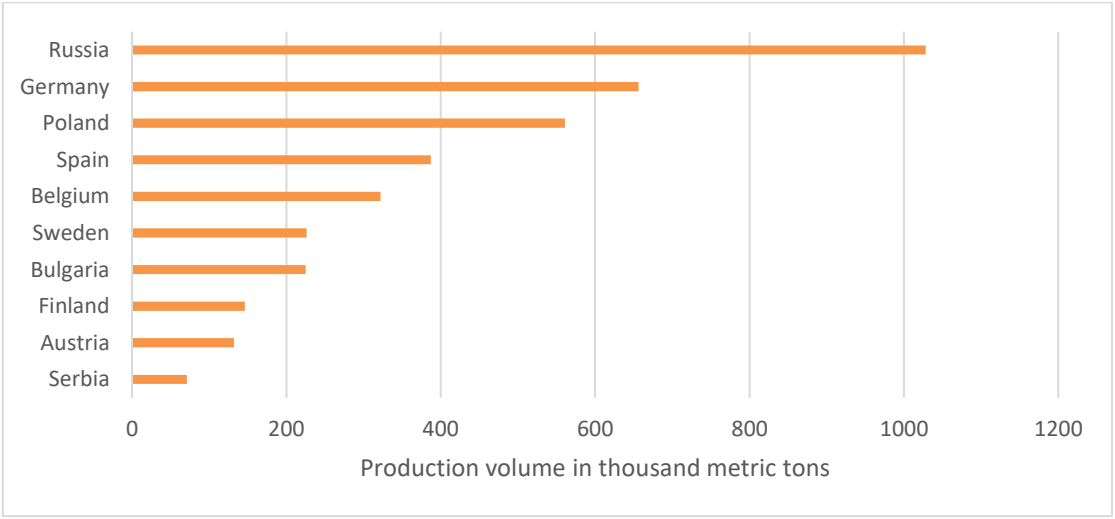
Consequently, copper, is recognised as a key material for low carbon solutions like renewable energy applications and electric vehicles. Less well known is that copper is a ‘carrier metal’ for a wide range of other non-ferrous metals of strategic importance for a climate neutral Europe. So, refining and recycling of copper is Europe’s most important route to access precious and critical metals. More than 20 other metals can be recovered from secondary copper production through the recycling of electronics waste and other complex products.

Figure 15 - Copper sector interlinkages, (Source: European Copper Institute)



Today, Chile is the world's top copper producing countries, followed by Peru, China, Democratic Republic of the Congo and the USA[21]. The main production sites in Europe are in Germany, Poland, Spain, Sweden, Finland, Belgium and Bulgaria.

Figure 16 - Refined copper production in leading European countries 2020, (Source: Eurostat)



Copper sector is represented in Europe by “European Copper Institute” which includes the world’s leading mining companies, custom smelters and semi-fabricators (represented by the International Copper Association, Ltd.) and the European Copper Industry. The European Copper Institute is part of an international network of industry associations, unified by a common brand and visual identity: the Copper Alliance.

Figure 17 - Copper Smelters(left) / Refineries(right) in EU, (Source: Copper Alliance)

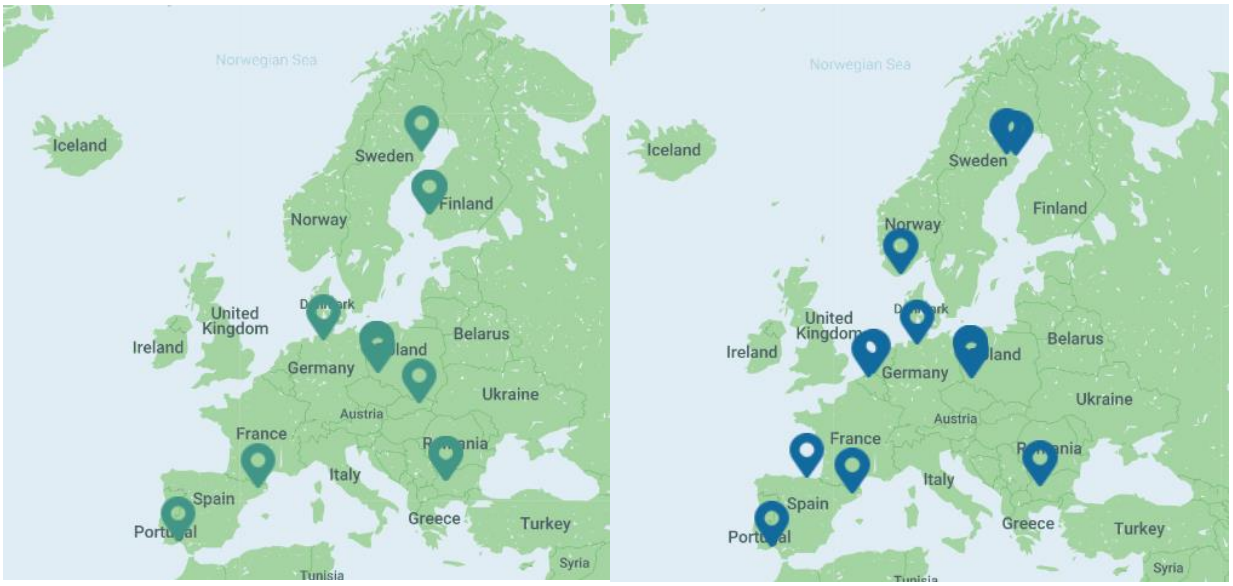


Figure 18 -Copper Recyclers in EU, (Source: Copper Alliance)



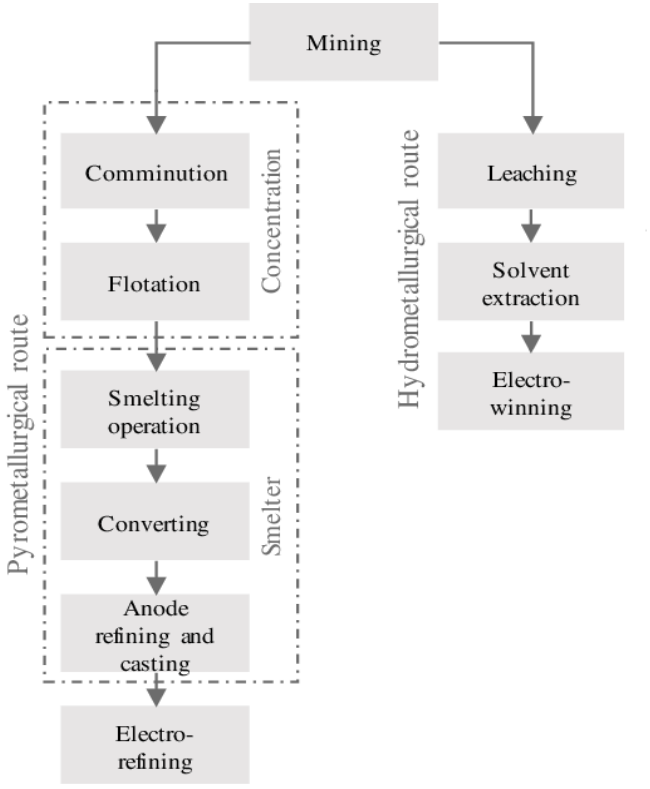
4.2 Production process

The primary production of copper takes place in three stages:

1. Mining and concentration of the ores
2. Conversion of the sulphides and other copper compounds to copper
3. Refining of copper

Primary copper can be produced by pyrometallurgical or hydrometallurgical processes (leaching). Worldwide, 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 [22].

Figure 19 - Production processes of copper, (Source: European Copper Institute)



The ore from the mine contains about 2% copper. To get at the copper the first stage is processing in huge cylindrical ball mills, so the ore is crushed, then ground into powder. The powdered ore is mixed with a special paraffin oil which makes the copper mineral particles water repellent. It is then fed into a bath of water containing a foaming agent which produces a kind of bubble bath.

The ore is enriched using a process called froth flotation. When jets of air are forced up through the bath, the water repellent copper mineral particles are picked up by the bubbles of foam. They float to the surface making a froth. The unwanted waste rock (gangue) falls to the bottom and is removed.

The froth is skimmed off the surface and the enriched ore (mainly the copper mineral) is taken away for roasting. The mixture of water, foaming agent and paraffin is recycled. Concentrates are next dried to reduce the moisture content from 7-8% to about 0.2% prior to the smelting process.

There are two types of dryers used for drying copper concentrates: hot gas rotary dryers heated by the off-gases from combustion and steam-heated coil dryers.

After this drying stage the enriched ore which is called copper concentrate now contains about 25% copper by mass. It is valuable enough to ship to other plants and other countries for processing. For example, China, Germany and Japan are major copper producers that use concentrate from around the world.

At this stage of the process, the chemical reactions begin. This stage is called roasting and during this stage the copper minerals convert into copper metal. The powdered, enriched ore is heated in air between 500°C and 700°C to remove some sulphur and dry the ore, which is still a solid called calcine.

Following this comes the smelting processes, during which the calcine is heated to over 1200 °C with fluxes such as silica and limestone. The calcine melts and reacts with the fluxes. Some impurities form a slag (such as $FeO.SiO_2$), which floats on the surface of the liquid (like oil on water) and is easily removed. The smelter for sulphide ores produces sulphur dioxide gas. This is scrubbed from the flue gases to make sulphuric acid for leaching copper from oxide ores. Scrubbing sulphur dioxide also serves in the protection of the environment.

The roasting and smelting process is typically carried out simultaneously in a single furnace to produce melt that can be separated into matte (copper sulphide typically containing 60 – 65% copper) and a slag rich in iron and silica. The sulphur-based gases generated by this process is directed to on-site acid plants to be used as a raw material in the production of sulphuric acid.

The flash smelting process uses oxygen enrichment to produce an autothermal (autogenous) or nearly autothermal operation. The matte produced in the smelting furnace is then fed into the conversion process. The conversion process converts matte into blister copper (typically 98.5% copper) by oxidizing the copper sulfide with an air/oxygen mixture. The reaction is strongly exothermic and the process heat can be used to melt copper scrap without the addition of primary heat. [8]



The blister copper is further purified by fire refining in anode furnace. The refining step involves the addition of air to oxidize impurities and final traces of sulphur and then a reducing agent to reduce any oxide present. The cast anodes are then subject to electrolytic refining. to produce high purity (99.99%) copper (cathodes). An electrolytic cell is used which consists of a cast copper anode and a cathode placed in an electrolyte that contains copper sulphate and sulphuric acid. At a high current density and low voltage, copper ions are dissolved from the impure anode and pass into solution from where they are deposited onto the cathode. During electrorefining, other metals contained in the anodes are separated and further recovered; less noble metals like nickel are dissolved in the electrolyte and more noble metals like the precious metals, selenium and tellurium form an anode slime that settles in the electrolytic cells. The slags produced from primary smelting and converting stages are still rich in copper and are subject to a number of slag treatment processes. The most used slag treatment/cleaning processes are electrified e.g. electric furnace or slag flotation. The slag fuming process is a specific process that may need measures to further reduce carbon emissions [1], [23].

The hydrometallurgical process is usually applied to oxidic or mixed oxidic/sulphidic ores at mine sites where there is sufficient space for the leaching and treatment areas. The process is particularly useful for ores that are difficult to concentrate by conventional means and which do not contain precious metals. In this process, known as SX-EW (solvent extraction/ electrowinning), 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 concentrates 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. When a current is passed, copper is then deposited at the cathode forming copper cathode [8],[22]. The process can be used on poor ores, containing as little as 0.1% copper and for this reason, leaching extraction is growing in importance. It is estimated that SX-EW will represent over 20% of total global copper refined production in the future. However, because this process should ideally be performed near mining operations, it is rarely (< 3%) used in the EU.

The secondary copper is produced by pyrometallurgical processes. The process stages used depend on the copper content of the secondary raw material, its size distribution and the other constituents. As in primary copper, the various stages are used to remove these constituents and to recover metals to the greatest possible extent from the residues that are produced [1],[23]. Scrap quality has a high impact on the energy consumption and direct emissions of secondary copper



furnaces. Secondary copper production can be more energy intensive compared to primary production which is very efficient due to exothermal processes. It has however a lower environmental footprint from a life-cycle perspective. During the recycling of copper others metals, mainly zinc, lead, tin, iron, nickel and aluminium, as well as precious metals are recovered.

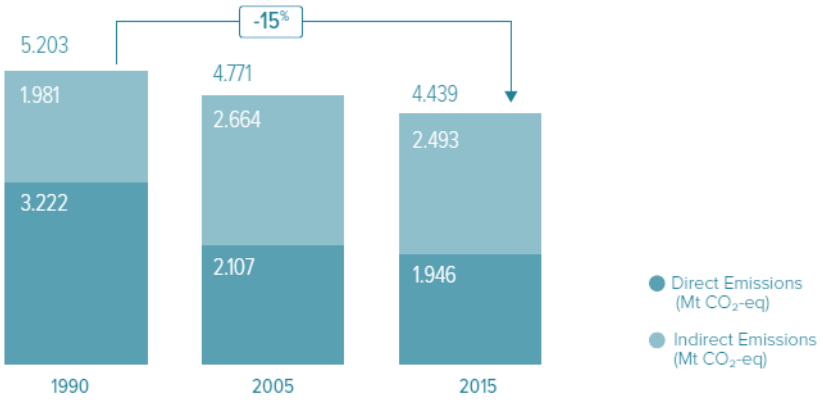
4.3 Energy consumption and GHG emissions

Copper production requires energy in most stages, with the energy used in the electrolytic process being the most significant.

Approximately 1.5 MWh electricity is used to produce a tonne of copper in the EU. The total energy use is around 12 GJ/t or 3.3 MWh/t of copper. Therefore, almost half of the energy use in copper production comes from electricity. Moreover, modernized smelter-refiners are even more electrified and use higher current densities during electrolysis, resulting in higher electricity consumption.

The hydro-metallurgic method on the other hand, is less energy intensive than the conventional method but it is remarkable that the electrowinning of copper requires considerably more electrical energy than the electrorefining process. Steps are under development to reduce the energy requirements of electrowinning by 40% by a modification of the anode reaction [1].

Figure 20 - Evolution of GHG emissions from EU28+EFTA aluminium production (Mt CO_2-eq), (Source: Eurometaux[1]*)*



Between 1990 and 2015 the emissions from copper production in the EU decreased by 15%. Direct emissions fell by 40% but indirect emissions went up by 25%. However, over the same period (1990-2015) copper production increased 40% (from 1.94 Mt in 1990 to 2.73 Mt in 2015). Hence the CO_2 intensity of copper production reduced significantly from 2.67 t CO_2/t copper in 1990 to 1.62 t CO_2/t copper in 2015 leading to a reduction of 40%. These shifts can be explained by important efficiency gains in copper production (60% reduction in energy use per tonne of copper since 1990 [20] in particular the shift to flash-smelting). This process requires a lot of oxygen and therefore higher

levels of electricity use for the production of oxygen, which explains the increase in indirect emissions. Further efficiency gains came from new and modernized furnaces, renovated electrical equipment, efficient drying technologies, (residual) heat recovery systems and energy management systems [1].

4.4 Energy efficiency and decarbonisation innovations

Aiming at energy efficiency and GHG emission reduction, the wider metallurgy sector has invested in research and study of new production techniques. Below are some potential opportunities specifically related to the copper industry.

4.4.1 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 is injected by compressed oxygenated air, prompting immediate endothermic combustion at 1100°C, without using any other fuels. 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. Use of a flash smelting furnace reduces the consumption of standard fuels due to the optimum utilisation of the heating value of the sulphidic concentrates and organic carbon present in copper concentrate. The TRL is estimated to be 8 [13].

4.4.2 Copper extraction using electrolysis

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 sulphide. 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 SO_2. Research is still at early stages and TRL is estimated to be 2-3 [13]



4.4.3 Alternative Fuels

Hydrogen can be considered as a replacement to coke or natural gas as the reductant in some pyrometallurgical processes of non-ferrous metals or as a reducing agent in the copper fire refining process. Hydrogen produced via electrolysis has the benefit of having oxygen as a by-product, which can also be used in some of the smelting processes (e.g. copper smelting). This can improve the business case of using electrolysis-based hydrogen as a reducing agent. However, hydrogen gas in general used as a reducing agent during smelting is not seen as candidate as it embrittles copper [13].

Given the high temperatures needed to make copper, biofuels are not currently seen as good candidates in replacement of thermal energy sources. With the development of new biofuels for jet fuel, this limitation may be overcome in the following years [13]. Use of synthetic fuels can be an option for use in copper smelters, but these must be cost-competitive.

4.4.4 Waste heat recovery – Aurubis case

Aurubis, in 2018 started the delivery of industrial waste heat from the Hamburg Aurubis plant to provide energy-efficient district heating to Hafencity East. For this purpose, Aurubis extracts heat that is formed when sulphur dioxide – a by-product of copper smelting – is converted to sulphuric acid. This industrial waste heat is nearly free of CO_2, and utilizing it will reduce CO_2 emissions by more than 20,000 t per year. About half of this reduction results from the replacement of natural gas used to produce steam on the Aurubis plant premises, while the other half is saved by delivering the waste heat to enercity. In Hafencity East alone, about 4,500 t of CO_2 will be saved each year in the final expansion (target: 2029). Aurubis will deliver the heat to its plant boundaries. Enercity Contracting Nord GmbH, a 100 % enercity holding located in Hamburg, will collect the heat, secure it and transport it further to the area that will use it [24].

Finally, CCS technologies have yet to be researched or developed specifically for the copper industry. It is expected that as the technology progresses and is adopted by other industries, it could also be applied to the copper industry.



5 Nickel

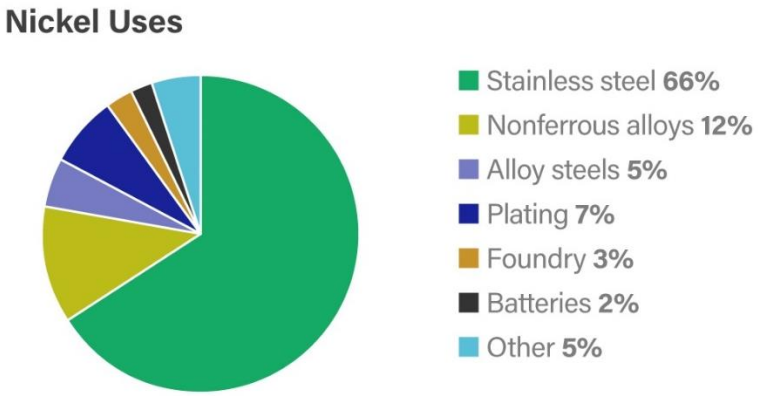
5.1 Introduction

Nickel is a naturally-occurring metallic element with a silvery-white, shiny appearance. It is the fifth-most common element on earth and occurs extensively in the earth's crust and core. Nickel, along with iron, is also a common element in meteorites and can even be found in small quantities in plants, animals and seawater.

The great importance of nickel lies in its ability, when alloyed with other elements, to increase a metal's strength, toughness and corrosion resistance over a wide temperature range. Nickel is therefore an extremely important commercial element. Given these beneficial properties, nickel is used in a wide variety of products. Most primary nickel is used in alloys, the most important of which is stainless steel. Other uses include electroplating, foundries, catalysts, batteries, coinage and other miscellaneous applications. Nickel is found in transportation products, electronic equipment, chemicals, construction materials, petroleum products, aircraft and aerospace parts and equipment, and durable consumer goods.

Nickel is a vital metal for industrialised societies but it is also vital to the climate neutrality because is an essential enabler for low carbon economy. In particular nickel-containing materials, especially stainless steel, are widely used for several renewable energy technologies.

Figure 21- Nickel uses, (Sources: Accure Group Holdings)

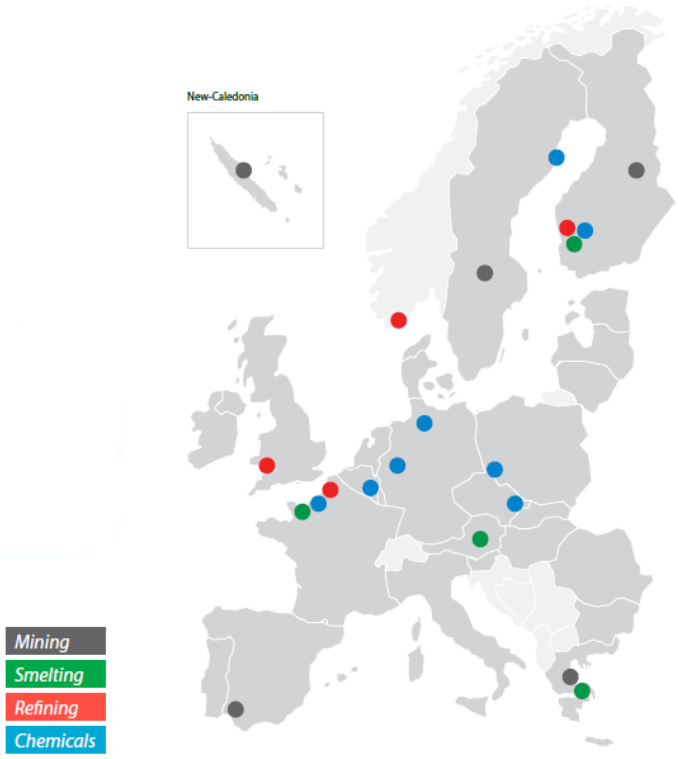


The nickel sector in Europe is relatively small. Nonetheless, it employs 4,700 persons and has an annual output of EUR 9.2 billion, with world class installations in Norway, Finland, the UK and France. Primary nickel production in Europe (including Norway) is 211 kt or 9.6% of global total primary production for 2018 [2]. Secondary nickel production in Europe amounts to 29.2% of the global secondary nickel production (200 kt out of 685 kt), with recovery rates being second only to that of

the secondary aluminium sector.

Currently, there is no dedicated European association for nickel, however the sector is represented (along with other non-ferrous metal industries) by Eurometaux as well as by the Nickel Institute (www.nickelinstitute.org), a global association of primary nickel producers.

Figure 22 - Nickel plants in EU, (Source: Nickel Institute)



5.2 Production process

Nickel is produced from oxidic (laterite and saprolite) or sulphidic ore. About 60 % of the nickel comes from sulphide deposits and 40 % from oxide deposits. There are several variations in the processes used to produce nickel from these ores and these variations are dependent on the grade of the concentrate and also on the other metals that are present in the material.

Three main methods are used for the treatment of nickel sulphidic ores:

1. The Inco method, where the concentrate after oxidative roasting melts in electric furnaces.
2. The Outokympu method, where the concentrate after drying melts in flash furnaces.
3. The Sherritt method, where the concentrate is extracted and reduced to precipitate nickel and cobalt.

If the ore contains a significant amount of Cu, then the production of matte using a converter is mandatory. Separation of matte Ni and Cu is carried out either by slow cooling of the matte or by roasting and extraction with H_2SO_4.

Two methods are used for the hydrometallurgical treatment of matte:

1. The Amax method
2. The Sherritt method

In the Amax method the matte is extracted using sulphuric acid from the Cu extraction circuit. Metallic Ni is precipitated from the aqueous solution using H_2 gas and temperature rise.

The Sherrit method consists of extraction with ammonia followed by boiling with H_2SO_4 to remove Cu. The nickel is then reduced to autoclaves under pressure where nickel powder and briquettes are produced [25].

Four main methods are used for the processing of lateritic nickel ores:

1. Melting to produce matte. It is the first industrial application of pyrometallurgical treatment of oxidized Ni ores.
2. Direct smelting of the ore for the production of ferronickel.
3. Reduction roasting and extraction with ammonia to produce nickel oxide.
4. Extraction with sulphuric acid in autoclaves under pressure to produce briquettes and nickel powder (Pressure Acid Leaching method, PAL).

In general sulphide ores can be separated using froth flotation and pyrometallurgical processes to create nickel matte and nickel oxide. These intermediate products, which usually contain 40-70% nickel, are then further processed, often using the Sherritt-Gordon Process.

Lateritic ores are usually treated with hydrometallurgical processes. Lateritic ores also have a high moisture content (35-40%) that requires drying in a rotary kiln furnace. High pressure acid leaching (HPAL) is one of the most common treatment processes of lateritic nickel ores.

Regarding secondary production, nickel scrap can be used in melting processes as addition to refined nickel. Moreover, efficient recycling of nickel takes place in the stainless- steel industry, which is the most importance nickel consumer. In 2010, around 43% of all nickel used in EU came mainly from recycling of stainless steel [5].

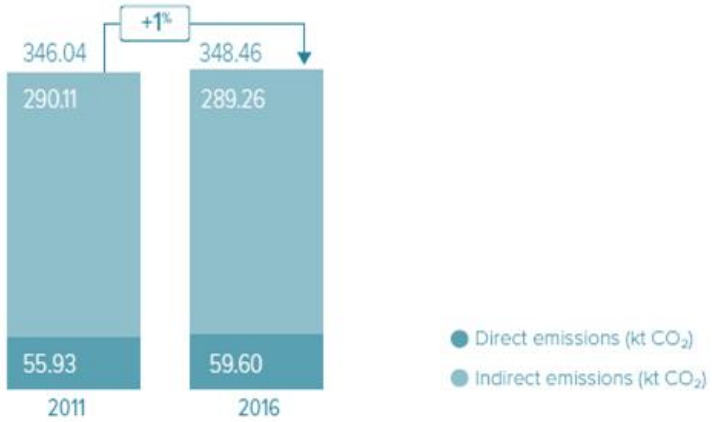
5.3 Energy consumption and GHG emissions

Nickel production in Europe is diverse with production in Norway and Finland being very electro-intensive. Sites in France and the UK are much smaller and less electro-intensive.



In particular, nickel refining is highly electro-intensive at 5-5.5 MWh/t nickel product. But also, processes related to the flash-furnace, can consume high levels of electricity up to 2.6-2.8 MWh/t nickel, 75% of which is related to slag treatment [26].On average, the energy use for nickel producers in Europe is 70-80% electricity and 20-30% natural gas [5].

Figure 23 - CO_2-eq emissions in Nickel production, (EU28 + Norway) (Source: Eurometaux[1]*)*



Between 2011 and 2016, the emissions from nickel production remained stable (from 346 kt CO_2-eq in 2011 to 349 kt CO_2-eq in 2016 in the EU28 and Norway). The CO_2 intensity was reduced by 5% over the same period (from 1.91 to 1.84). Given the electro-intensity of nickel refining, the indirect emissions represent at around 85% by far the highest share of overall CO_2 emissions. Another significant fact is that most of the nickel produced in Europe is high purity (nickel class I, nickel content >99%). Other nickel products such as ferro-nickel and nickel pig iron are mostly produced outside of Europe, with most nickel pig iron being produced in China. Ferronickel and nickel pig iron have a lower nickel content ranging from 4-15% (nickel pig iron) to 30% (ferronickel). The specific GHG emissions differ significantly with class I nickel production at 7.8 kg CO_2/ kg nickel, 32.8 kg CO_2/kg nickel in ferro nickel, and between 70 kg and 98 CO_2/kg nickel in blast furnace and electric arc furnace nickel pig iron production respectively [27].

5.4 Energy efficiency and decarbonisation innovations

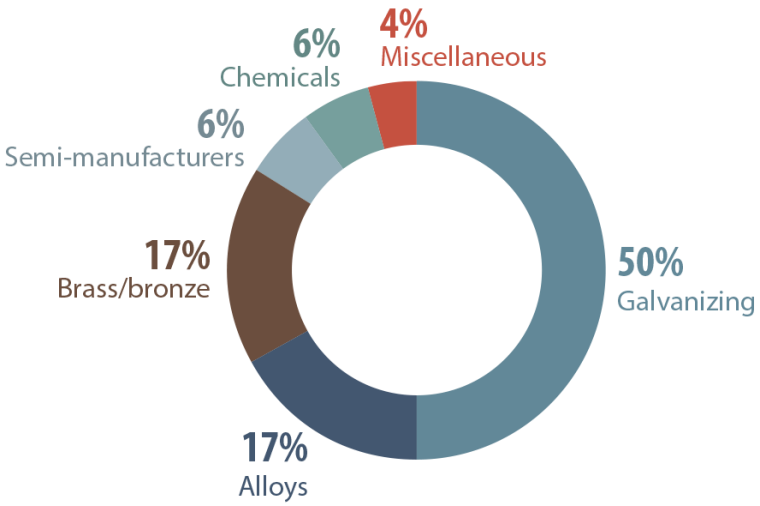
Limited information on innovations regarding energy efficiency and GHG mitigation specifically developed for the nickel industry are available. Electrification of various processes is considered as a potential solution for the replacement of fossil fuels: e.g. electric heating as a replacement to fossil fuel heating in auxiliary processes (e.g. boilers) and electrification of the production of technical/industrial gases (longer term).

6 Zinc

6.1 Introduction

Zinc is the fourth-most used metal after iron, aluminium, and copper. With good abrasive resistance, corrosion resistance, castability, and room temperature mechanical properties, zinc can be made into various alloys with many other metals. Mainly, it is used in the form of galvanization, zinc-based alloys and zinc oxide. It has applications in the automobile, construction and shipbuilding industries, light industry, machinery, household electrical appliances, batteries and other industries. End uses include a wide range of applications, the most important being steel protection against corrosion and abrasion and for the automobile, appliance and building industries as it enhances the longevity of steel structures. Zinc alloys (e.g. brass, bronze, die-casting alloys) and zinc semis are respectively the second and third major consumption areas with applications also in the building, appliance and car industries.

Figure 24 - Uses of Zinc, (Source: Government of Canada, https://www.nrcan.gc.ca/)



Sulphide zinc ores are widely distributed throughout the world. The major deposits are found mainly in North and South America (Canada, US, Mexico, Peru, Bolivia), Australia, Japan and China. There are also significant deposits in South Africa, Iran, Spain, Scandinavia, Spain, North Macedonia, Russia and Germany.

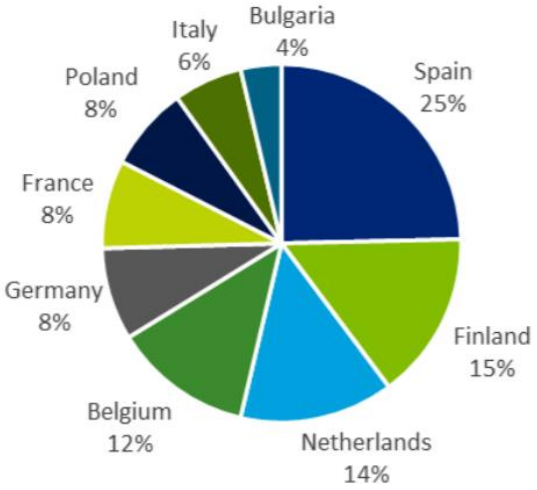
The EU only has a small share (5.44%) of the global zinc ores; consequently 71% of zinc (concentrate) is imported from other countries. Still, the EU has an important share of the global primary zinc production. Primary zinc production in the EU stood at 1,699 kt or 13.4% of global total primary production in 2016 [28]. In the same year, secondary production of zinc stood at 296 kt as

compared to 1,563 kt global secondary production (18.94%).

Zinc is supplied to the market in various qualities, the highest quality being special high-grade (SHG) or Z1 which contains 99.995 % zinc while the lowest quality good ordinary brand (GOB) or Z5 is about 98 % pure. The sector produces extrusion products such as bars, rods and wires (mainly brass); rolling products such as sheets and strips; casting alloys; and powders and chemical compounds, such as oxides [23].

The zinc industry in Europe is well established with 12 plants located regionally providing direct employment to around 5,000 people and indirect employment to more than 50,000 people with a turnover of EUR 5 billion approximately [29]. Apart from Eurometaux, the sector is represented by the International Zinc Association (IZA - www.zinc.org), which brings together industries representing 60% of the global zinc production and numerous affiliate members from key zinc consuming end-user groups.

Figure 25 - EU refined zinc production average 2012-2016, (Source: BGS, 2018)



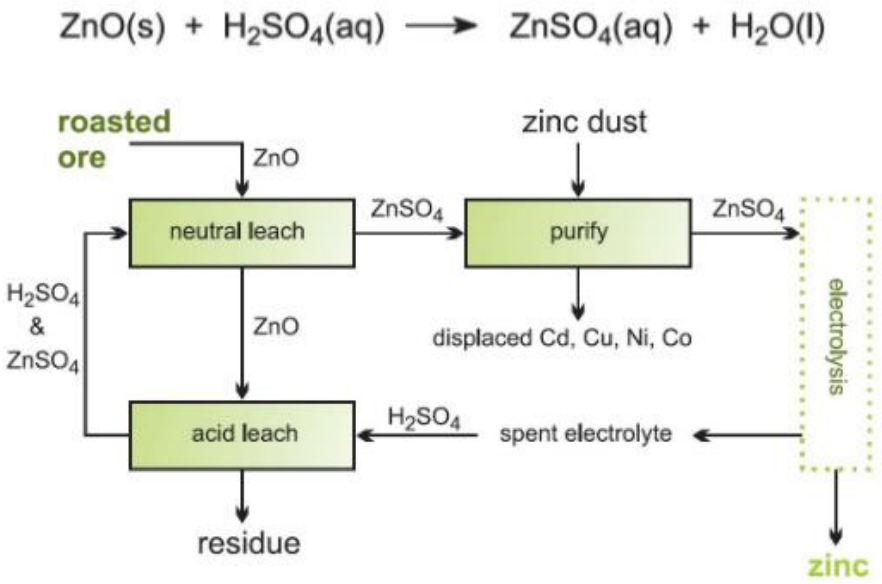
Zinc is essential for the transition to a climate neutral economy and will contribute in different ways given that zinc prolongs the lifetime of steel constructions and vehicles, there is lesser consumption of primary raw materials, lower energy consumption and reduced CO_2 emissions. A galvanized steel structure of 500 t actually saves ~ 57 Tonnes CO_2 emissions compared with an “equivalent” painted system [30]. Both zinc and platinum are used in fuel cells for grid storage and micro-grid generation. Zinc-based energy storage systems such as primary zinc-carbon and alkaline batteries, zinc-air and zinc-silver “button cell” batteries would be of critical importance too. Large zinc-based energy storage systems ensure a constant energy supply from non-constant energy sources (wind and solar). Moreover, zinc helps protect transmission towers, offshore windmill towers and carrier constructions for solar panels from corrosion, thus ensuring their reliable functioning over a long period of time.

6.2 Production process

Nearly all zinc is obtained from sulphide ores, which also usually contain lead, cadmium and other metals such as iron and silver. The most commonly occurring ores are sphalerite, also known as zinc blende (ZnS), and another variety of sphalerite called marmatite which contains significant quantities of iron sulphides.

There are two methods of smelting zinc: the pyrometallurgical process and the hydrometallurgical process; over 90% of hydrometallurgical process is in electrolytic plants using electrolysis process. Both of these processes have the same first step: roasting. Roasting is a process of oxidizing zinc sulphide concentrates at high temperatures into an impure zinc oxide, called "Zinc Calcine".

Figure 26 - Hydrometallurgical production process (RLE), (Source: The essential chemical industry)



The electrolysis process, also known as the hydrometallurgical process, Roast-Leach-Electrowin (RLE) process, or electrolytic process consists of 4 steps: leaching, purification, electrolysis, and melting and casting. In the RLE route calcine (ZnO) is produced from zinc concentrates in a roasting process and a zinc sulphate solution (ZnSO4) obtained following the leaching. The purification process utilizes the cementation process to further purify the zinc. It uses zinc dust and steam to remove copper, cadmium, cobalt, and nickel, which would interfere with the electrolysis process.

Some plants operate a direct leach process on a part of the flow, which allows to by-pass the roasting step. Zinc sulphide ore roasting usually takes place in a fluidized bed furnace at around

1000˚ C, with air being blown in through a perforated bottom. The most important reaction is the conversion of zinc sulfide to zinc oxide. The oxidized zinc is dissolved in acid and other metals are separated as by-product from this zinc flow.

Zinc is extracted from the purified zinc sulphate solution by electrowinning, which is a specialized form of electrolysis. The process works by passing an electric current through the solution in a series of cells. This causes the zinc to deposit on the cathodes (aluminium sheets) and oxygen to form at the anodes. This process accounts for approximately one-third of all the energy usage of smelting zinc. The zinc deposit on the cathodes is stripped off, molten and cast into ingots. The metal is at least 99.95% pure.

It is possible to make very high purity zinc (99.995% pure) by adjusting electrolysis conditions such as temperature and current density. Metal of this purity is required for diecasting alloys containing aluminium, magnesium and copper.

The current pyrometallurgical process uses the Imperial Smelting Furnace, ISF, which was invented and developed at Avonmouth, Bristol. Due to its high energy and emissions costs is completely superseded in Europe by the electrolytic process. Even though ISFs still operate on other continents. It is capable of simultaneously producing zinc and lead from sinter (agglomerated oxides). Sinter is produced by roasting a mixture of zinc and lead concentrates, fluxing agents (sand and lime), and secondary materials. A blast furnace is charged with the sinter and hot coke. Coke acts as energy source and reducing agent. By-products of these processes include sulphuric acid, lead, precious metals, cadmium, copper, indium, germanium, nickel and cobalt.

Regarding to the secondary production, over 40% of the zinc used annually is from recycled metal. Much of this comes from zinc-coated steel which, for example, has been used for roofing and automotive. This is placed in the Electric Arc Furnace being used to recycle the steel. Zinc is relatively volatile and leaves the furnace with other gases. It is collected on cooling as zinc dust. Therefore, this dust is first processed in Waelz kilns to separate it from iron. Iron come out as a slag for construction and roads while zinc comes out as an oxide. This zinc oxide is further refined by zinc smelters in the process described above [1].

6.3 Energy consumption and GHG emissions

As said prior the ISF technology is more energy intensive, a fact that led to its fully supersession by the hydrometallurgical method (RLE). Energy use of ISF is more than 2.5 times higher compared to



RLE per tonne of zinc produced. The RLE process is much more electro-intensive with 4.17 MWh electricity needed to produce one tonne of zinc [1]. It is remarkable that EU zinc smelters have some of the lowest total average production costs among the countries compared and one of the highest productivities [31].

Figure 27 - Energy use per tonne of Zinc RLE/ISF, (Source: Brook Hunt a Wood Mackenzie Company[1]*)*

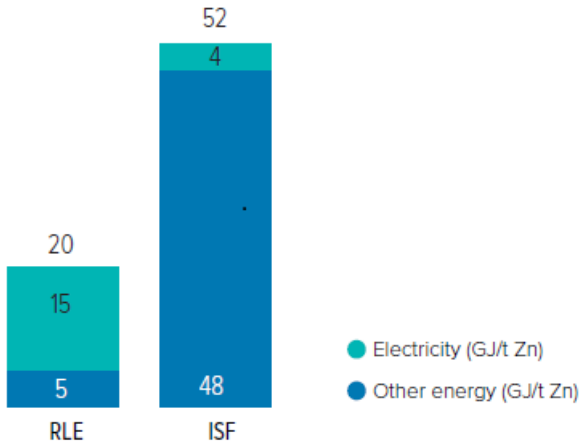
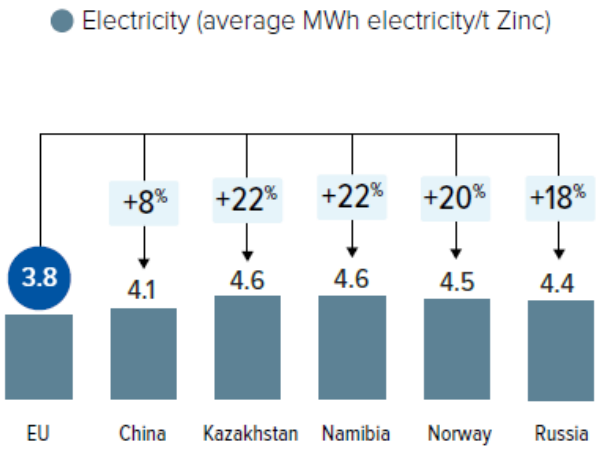


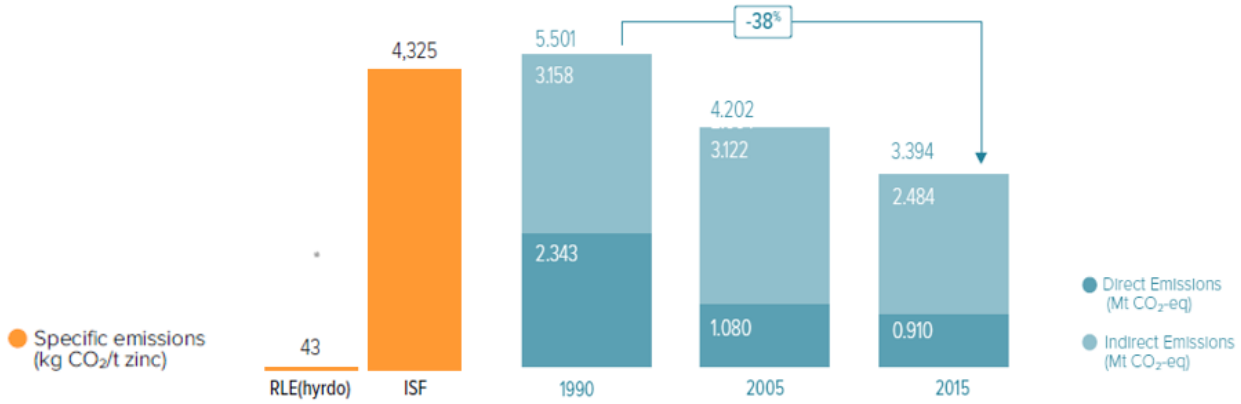
Figure 28 - Electricity use per ton of Zinc (MWh/t) (2013), (Source: JRC, 2016)



In 1990, there were 22 zinc refineries in the countries of the EU27 plus Norway producing zinc metal using three different technologies: a) 6 plants with a pyrometallurgical Imperial Smelting Furnace (ISF) technology; b) 14 plants with Roasting-Leaching-Electrolysis process (RLE), full hydro; c) 2 plants with RLE process, combined hydro and pyro processes. After 2000, a number of plants were closed down, mainly smelters using the ISF technology. The major reason for the closure of plants using the ISF technology was their comparatively higher energy consumption leading to much higher

production costs. In 2015, there was only 1 ISF plant left in the EU providing only 3% of the EU production, down from 18% in 2004. Presently, most zinc is produced using the RLE, full hydro process. The RLE, full hydro process has the lowest energy consumption and 94% of the consumed energy is electricity – with 84% of electricity consumed used in the electrolysis stage of the zinc refining process. Today, electricity represents 85% of all energy used in the production of zinc [30].

Figure 29 - (Left)Direct emissions of Zinc production (RLE/ISF), (right) CO_2-eq emissions from Zinc production (Mt CO_2-eq) in the EU and Norway, (Source: Eurometaux[1])



Direct emissions of ISF are a factor 100 higher compared to RLE with hydrometallurgical treatment of leaching residues [10]. Between 1990 and 2015 the GHGs from zinc production in the EU28 and Norway fell 38%. Major reductions in direct emissions (62%) came due to the shift from the coke intensive pyrometallurgical ISF process towards the more energy efficient electrolytic RLE process. Further emission reductions in zinc production will not be simple given that secondary raw materials in smelter feeds are increasing, which can lead to higher CO_2 emissions [1].

6.4 Energy efficiency and decarbonisation innovations

In the RLE, the full hydro process, the direct emissions have been basically constant since 1990. They mostly result from the combustion of fossil fuels for the heating of materials and solutions in the process. Most of the metal melting furnaces have already switched from gas heating to highly efficient electrical induction heating. This heat requirement is additional to the heat recovered in the process, all RLE smelters are equipped with a heat recovery system allowing the recovery of the heat generated during the roasting of the zinc concentrates. This process is exothermic and does not require external heat under normal operating conditions (except for furnace pre-heating after a shut-down). Here also it can be assumed that more efficient equipment will become available over the next 40 years, leading to an even higher heat recovery. In such a case the CO_2 emissions could be reduced by 50%, but such a reduction represents less than 1% of the total CO_2 level of 1990 [30].

For the pyrometallurgical processes, and mainly for the ISF process, the direct emissions constitute the major part. A reduction of those emissions will require the use of appropriate abatement technologies or CCS when available at an acceptable cost [30].



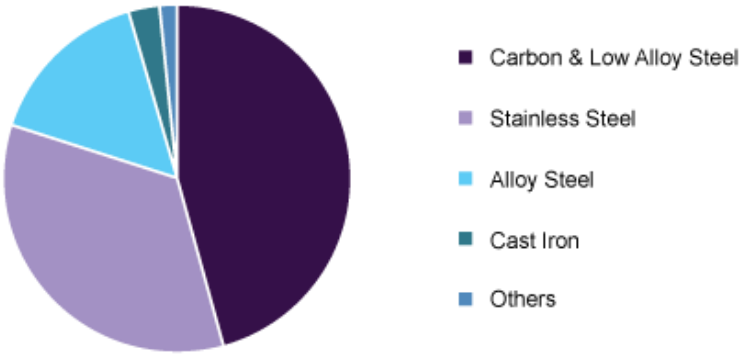
7 Silicon & Ferroalloys

7.1 Introduction

Despite the apparent contradiction in terms, the production of ferroalloys, which are mainly used as master alloys in the iron and steel industry, is considered part of the wider non-ferrous metals industry. Their alloying elements, like refractory metals, chromium, silicon, manganese and nickel, are all non-ferrous metals.

Ferroalloys are master alloys that contain some iron and one or more non-ferrous metals as alloying elements. Silicon is produced in the same metallurgical process as ferrosilicon and it is therefore considered a ferroalloy. Ferroalloys are used as deoxidizing elements in steelmaking and enable alloying elements such as chromium, silicon, manganese, nickel, vanadium and molybdenum to be safely and economically introduced into metallurgical processes, thus giving certain desirable properties to the alloyed metal, for instance increased corrosion resistance, hardness or wear resistance.

Figure 30 - Ferroalloys applications (Source: Grand View Research)



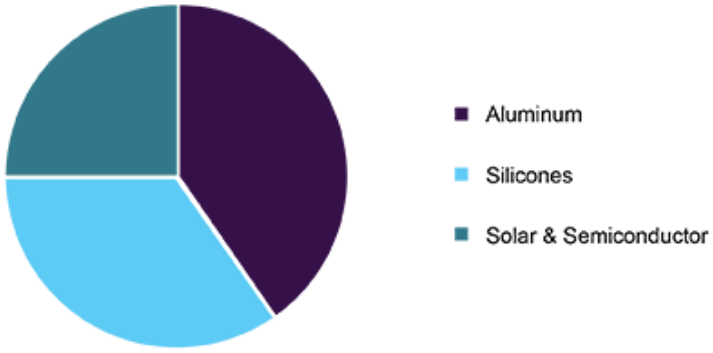
The importance of ferroalloys increased with the progress of steel metallurgy, which demanded diversified alloying elements to achieve better controlled quantities in purer and more advanced steel qualities. The ferroalloy industry became a key supplier to the steel industry. Ferroalloys are mainly used as master alloys in the iron, foundry and steel industry to improve their tensile strength, wear and corrosion resistance which hence help prolong the lifetime of steel-based infrastructure and vehicles thereby reducing primary material consumption, energy and emissions.

Silicon is a grey and lustrous semi-conductive element; it is the second most abundant element in the earth's crust (behind only oxygen) and the eighth-most common element in the universe. Nearly 30% of the weight of the earth's crust can be attributed to silicon. Naturally silicon occurs in silicate minerals, including silica, feldspar, and mica, which are major components of common rocks such

as quartz and sandstone.

As a semi-metal (or metalloid), silicon possesses some properties of both metals and non-metals. Like water - but unlike most metals - silicon contracts in its liquid state and expands as it solidifies. It has relatively high melting and boiling points, and when crystallized forms a diamond cubic crystal structure. Critical to silicon's role as a semiconductor and its use in electronics is the element's atomic structure, which includes four valence electrons that allow silicon to bond with other elements readily. Silicon is also used in lithium-ion batteries (anodes), photovoltaic (PV) thin cells, and wind turbine generators among the most relevant green tech applications.

Figure 31 - Silicon applications (2019), (Source: Grand View Research)



Silicon is used as an alloying element in aluminium and in the chemical and electronic industries, solar cells, etc. In general, silicon and ferro-alloys feed into the steel, ceramics, cement, chemicals, fabricated metal products, other non-ferrous metals, and rubber and plastics sectors.

Silica Fume, the by-product of the production of silicon and ferrosilicon improves the sustainability of buildings and contributes to reducing their carbon footprint.

Ferroalloys and silicon are essential elements in the production of a range of materials and have no substitute. Metallurgical silicon (also called “silicon metal”) has been recognized by the European Commission as a CRM due to its economic importance in a wide range of applications, for many of which there is no possible substitute. Finally, silicon and ferroalloys are key enablers for a low-carbon economy in Europe and for sustainable solutions globally.

Silicon and ferroalloys are produced in the EU by 32 plants in 10 countries, with approximately 90 furnaces in activity, a global turnover of € 2.7 billion, a Gross Value Added of € 480 million and a workforce of 4,300 people [32]. The sector is represented apart from Eurometaux by the Euroalliages (http://www.euroalliages.com/) which is the European association of ferroalloy and silicon producers. The total membership includes 21 companies, operating nearly 35 plants in 12 different countries.

Figure 32 - Ferroalloys/Silicon plants in the EEA (Source: Internal data Euroalliages)



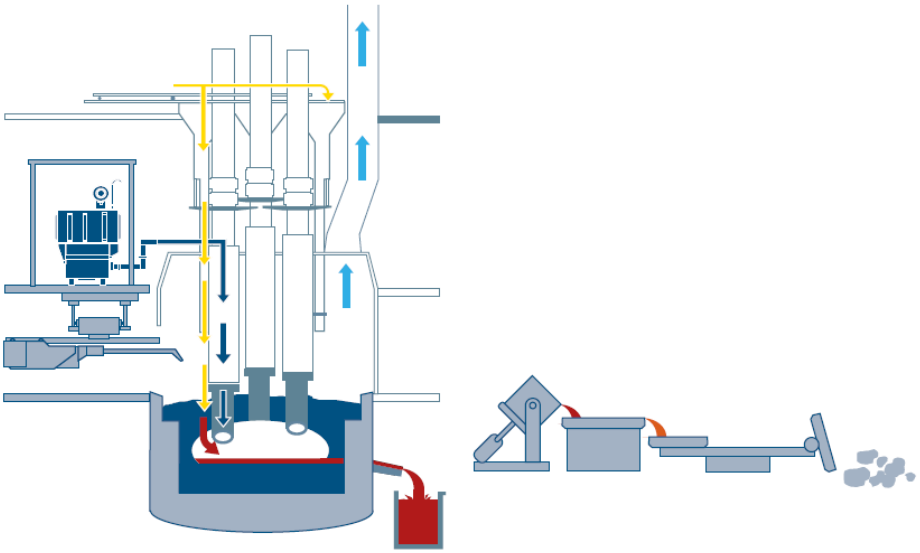
The leading producers of ferroalloys in 2014 were China, South Africa, India, Russia and Kazakhstan, which accounted for 84% of the world production. EU is a net importer, as imports contribute 73% of total consumption.

7.2 Production process

Ferroalloys and silicon are principally produced in submerged EAF (electric arc furnaces). The basic process involves the carbothermic reduction of oxidic ores or concentrates, in which carbon coming from a reductant in the form of coke (metallurgical coke), coal or charcoal is normally used as a reducing agent. In the EAF, the heating process is accomplished by passing current through electrodes suspended in a cup-shaped (refractory-lined) steel shell, which are progressively consumed. The carbon from the reductant (coke, coal or charcoal) captures the oxygen from the metal oxides to form CO_2, while the ores are reduced to molten base metals which then combine in the solution.

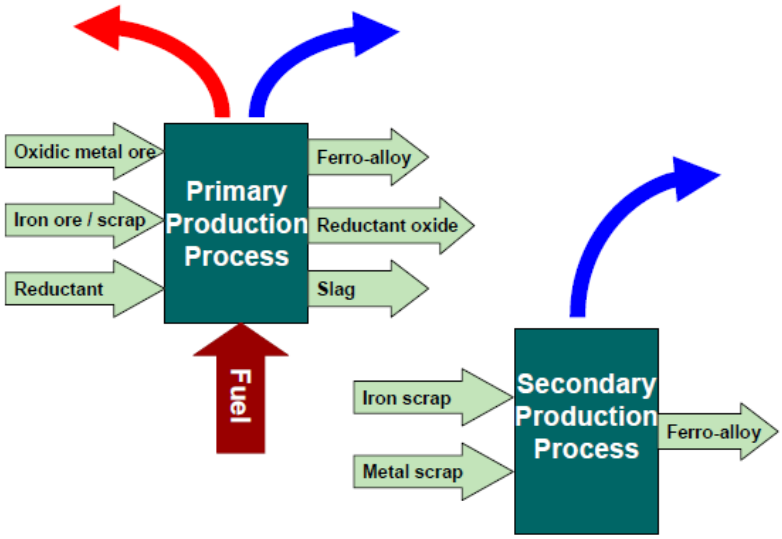
In silicon production, one of the important by-products of this process is silica fume; as aforementioned, silica fume can be used in the construction industry.

Figure 33 - Submerged electric arc furnace (Source: Elkem[32]*)*



The raw materials can also be recovered from scrap, which is most often the case for the iron share of the composition, which comes from iron and steel scrap, but also for the alloying element itself, titanium for example. Residues from steel mills like electric arc furnace and converter filter dust, as well as shot blasting and grinding dust, are important secondary raw materials which have increasing significance.

Figure 34 - Simplified process scheme for primary (top left) and secondary (bottom right) production process of ferroalloys [33]



Product quality requirements impose major constraints in the choice of raw materials such as coal and cokes. Natural gas cannot be used as a reducing agent because smelting needs elementary carbon.

7.3 Energy consumption and GHG emissions

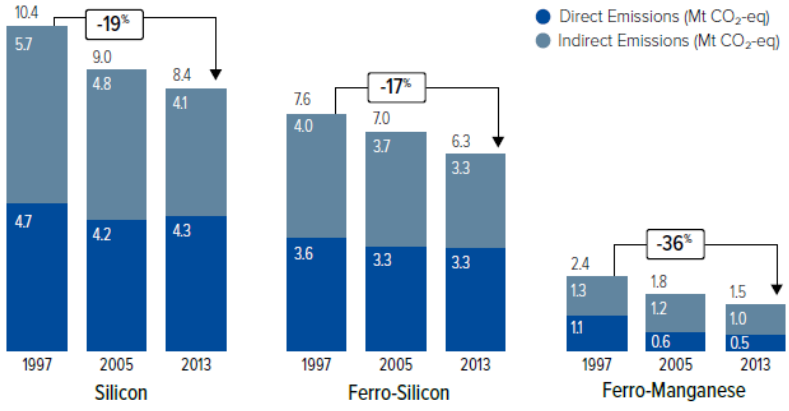
The energy consumption per ton of metal differs greatly from one ferro-alloy to another. The production of ferro-alloys is a highly energy-consuming process because high temperatures are needed for the reduction of metal oxides and smelting. Factors affecting energy consumption are, among others, the quality of raw materials (such as ores, quartz and reducing agents) and their pre-treatment before smelting, the utilisation of energy reaction, as well as the heat content of the processes.

Figure 35 - Historical figures electricity consumption, (Sources: Euroalliages[32]*)*

	Electricity Input (MWh)		
Data per tonne produced (EU+EEA):	1997	2005	2013
Silicon	13.2	12.1	12.4
FerroSilicon	9.2	9.3	8.9
FerroManganese	2.9	3.0	3.0

Ferroalloy and silicon production are energy- and in particular electro-intensive processes. Silicon production requires 12.4 MWh/t of electricity, Ferro-silicon 8.7 MWh/t and Ferro-Manganese 3 MWh/t [32].

Figure 36 - Specific direct and indirect CO2 emissions for Silicon (left), Ferrosilicon (middle) and FerroManganese (right) (Source: Euroalliages[1]*)*



Ferroalloys and silicon production results in both combustion (heat generation) and process emissions (carbothermic reduction of metal oxides) which are the major source of carbon dioxide (CO_2). The direct emissions of silicon and ferro-alloys production are the result of the metallurgic reduction process. It is estimated that total CO_2 emissions from silicon in the EU were 1.6 Mt in 2013and 0.4 and 1.5 Mt for respectively Ferromanganese and Ferro-silicon. Specific CO_2 emissions

for silicon production reduced 19% between 1997 and 2013, 17% for Ferrosilicon and 36% for Ferro-Manganese. Over the past years, consolidation took place over these sectors together with plant closures of less efficient installations. Furthermore, significant investments to improve energy efficiency have been made [32].

7.4 Energy efficiency and decarbonisation innovations

Although the sector of silicon and ferroalloys is fully electrified, since carbon is used in the process only for its chemical properties and not for its energy content, significant efforts have already been made in the industry to achieve energy efficiency to further reduce their environmental footprint. Such an example is the recent project of the installation of an ORC (Organic Rankine Cycle) to transform waste heat into electricity. Apart from this the are some other interesting potentials aiming to reduce the CO_2 footprint.

7.4.1 Carbon capture and utilization (CCU): The Algae Project

The industrial part of the project started in January 2015 in the production line of ferrosilicon producer Finnfjord AS in Norway. The project is a cooperation between The Arctic University of Norway and Finnfjord AS, and is at present financed by Norwegian Regional/Government Funds in addition to the cooperation partners. The project concept covers the production of diatom biomass by sequestration of CO_2 and NOx from factory fumes and differs from other conventional initiatives with respect to the choice of organisms, photobioreactor type, illumination, cultivation technology and processing. The main product is fish feed, but bioprospecting and other applications are included. The ground-breaking feature is the integration of the “mineral world” and the “organic world” within the same industrial site by linking the “mineral” and the “organic” value chains with the conversion of CO_2 to fish fodder or fuel [32]. At present the project has the world’s largest vertical column photobioreactor (300 000L) running, and the biomass is being tested as eco-feed for aquacultured salmon.

7.4.2 Carbon Capture Storage (CCS)

In the case of CCS, the non-ferrous metals industry could benefit from innovations that are pioneered at larger process installations in other industries. For instance, the Steelanol project by ArcelorMittal, which uses a bacteria-based process to turn blast furnace gas into ethanol, could possibly find applications in some non-ferrous metals smelting processes and in ferro-alloys or silicon production.

The most interesting application of CCS would be in silicon and ferro-alloys carbo-thermic reduction processes due to the high carbon-monoxide concentration in flue gases. CCS in combination with use of bio-based carbon could even make silicon and ferroalloys production CO_2 negative, for its



direct emissions [1]

8 Challenges and potential measures

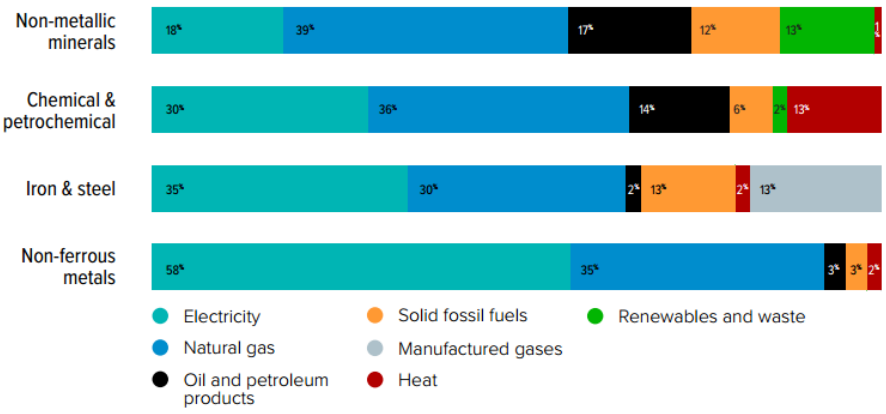
The non-ferrous metals industry in Europe is placed in the forefront of the transition to climate neutrality by 2050. Non-ferrous metals are an integral part of already known low-carbon : hybrid, electric and fuel cell vehicles, solar PVs, wind turbines, thermal systems, battery storage and others. Future consumption of non-ferrous metals is estimated to increase tremendously over current levels, in some cases by up to 300%.

The sector has been an early mover in terms of emissions and energy efficiency as major steps have been taken to reduce direct and indirect GHG emissions by 60% since 1990. At the same time non-ferrous metal industry has fully embraced the circular economy since has already achieved high recycling rates and trying to increase them further.

Since the path to 2050 is very short in terms of investment cycles and depends primarily on the decarbonisation of the EU's power sector, crucial decisions need to be taken right now in order to allow the EU non-ferrous metals industry to remain competitive, reliable and stable. Toward this transition to carbon neutrality, EU non-ferrous metal industries are facing many challenges and barriers which are not depended on them.

First of all, the non-ferrous metal industry is **highly electro-intensive**. This fact means that it has already achieved a remarkable reduction of indirect GHG emissions and therefore a reduction in its carbon footprint, through the increasing decarbonisation and renewable energy uptake in the European power sector. On the other hand, this points that non-ferrous metals industry is extremely sensitive to **electricity prices,** which affect its economic performance and **competitiveness**.

Figure 37 - Relative shares of energy carriers in the final energy use of different EII sectors



This sensitivity is connected with the fact that although the non-ferrous industry is not the largest absolute consumer of electricity compared to other energy intensive industries, it has the highest share of electricity - reaching 58% - in its final energy use. Therefore, even a small increase in electricity prices could seriously impact the competitiveness of EU producers against producers outside Europe.

In order to remain competitive, the EU non-ferrous metals production has gained **regulatory relief** in electricity pricing. This relief has a great importance because the cost of having to pay all regulatory price components would completely consume the gross added value and even turn it negative. However, there is no long certainty regarding the regulatory relief. Today the decision on indirect cost compensation is taken at Member State level and can change from year to year (e.g. linked to the availability of budgets). This creates a highly **uncertain investment climate** for measures related to energy savings or investments in new production technologies.

EU pricing remains competitive due to the **high productivity** of non-ferrous metals production in the EU and in particular the high level of energy efficiency achieved, as well as the **high recycling rates** of EU. In addition, CO_2 costs are reduced due to the low CO_2 intensity of production because of the efficiency of production but also due to the low CO_2 intensity of electricity production. The above competitiveness should **not be taken for granted** as future increases in energy prices will lead to reduced competitiveness of European non-ferrous metals since on the one hand it will be difficult for European producers to achieve a further increase in productivity, while on the other hand their competitors will start seeking ways to improve the efficiency of their own production.

Another important problem facing European production is the fact that although metals are traded globally or at globally consolidated prices, this does not mean that their production costs are the same. There are major **state-aid interventions** (e.g. bailing out production over-capacity) and support (e.g. subsidies) in metals production outside of the EU, in particular in China. While this does not necessarily imply higher imports into Europe, it will depress global metals prices and the possibility for European metals producers to compete on a level playing field.

In addition, there are **regulatory and other interventions** that have an important impact on production costs. Such interventions are the existing import and export taxes and duties. Also, numerous environmental regulations on issues such as pollution control (e.g. the Industrial Emissions Directive - IED), waste (including treatment and recycling),and the protection from harmful substances for the environment and human health (REACH) have an impact that is felt across the whole non-ferrous



metals industry in terms of additional costs, constrained recycling and reduced efficiency. Discriminatory public procurement policies in some major countries mean that EU companies lack a fair chance, a fact aggravated by a growing protectionism in third countries.

Taking into account all the above and the major investment efforts to achieve a higher environmental performance in EU, it is obvious why these efforts have led European industry to incur an **economic disadvantage** compared to third country producers. The sector is struggling against a background of barely sustainable and **unfair international competition** with companies that do not abide by the same environmental, social and financial standards, and consequently do not bear comparable costs.

Finally, regarding the process, although a significant way to reduce emissions for an energy-intensive industry is to **use RES**, this use is constrained by the availability, the reliability and most of all the cost of these energy sources.

In order for the European non-ferrous metals industry to remain viable and competitive it is important that EU policies take some measurements and apply solutions that will boost the economy and consolidate the position of the industry in the face of these barriers and obstacles.

First of all, the **policy** regarding the limitation of carbon footprint should be **feasible and balanced** in such a highly competitive and dynamic international environment.

Energy efficiency is a key element of competitiveness for every energy-intensive industry. Therefore, continuous efforts should still take place in order to explore creative solutions, adapted to local conditions, allowing both improved emissions reduction and energy efficiency.

As far as concerns the great amounts of electricity that requires the production of non-ferrous metals it is important to ensure a **price stability** of electrification because otherwise a highly uncertain investment climate will be created.

Together with the price stability it is necessary to be given to the European industry of non-ferrous metals a **state support** in order to secure their viability because as forefront they are the first that will feel possible negative side effects. **Regulatory relief** for electricity prices is another way that will make the competition fairer by **giving motives** to European producers. It will therefore be essential to ensure that non-ferrous metals industries have access to competitively priced, stable and carbon-neutral electricity to power the road to a climate neutral economy.

For this transition and in the light of neutrality, it is important to start using **RES** with greater intensity. A smart design of EU renewables and industrial policies could create the conditions where long-term contracts in renewables could reduce the cost of investments and hence promote further investments



in renewables. For the non-ferrous industry producers, an extended use of renewable **Power Purchase Agreements (PPAs)** would be helpful. The PPAs could be both beneficial for the consumer because this creates a price stability but also for the electricity producer due to the guaranteed revenue stream which will reduce the risks of large investments and hence reduce the cost of capital. So, a positive regulatory framework for PPAs and long-term power contracts would be essential for electro-intensive industries.

Further to the greening of the electricity, the European non-ferrous metals industry should also take steps to further **reduce the carbon footprint of its heat requirements**. Steps have already been taken in this direction by several industries: substitution of coal by natural gas, combined heat and power production, waste heat recovery and other energy efficiency measures. However, a further emissions reduction grows more complicated: the industry will have to evaluate different options that are already available on the table or will reach a high TRL in the future: further electrification, green hydrogen and renewable gases as a substitute for natural gas, biomass / bioenergy and others.

Another approach that would be interesting and could offer solutions to industries that can reduce their carbon footprint only to some extent, is the concept of "**negative emissions**", that can balance any remaining, hard-to-mitigate positive emissions. This concept should be further explored and needs political and regulatory support to be implemented successfully. For the non-ferrous metals sector, investing in negative emission projects may provide solutions for mitigating process GHG emissions, especially if the technologies that are now under development for reducing them fail to be market-ready by 2050.

During this transition, the high demand for metals will have as a result the creation of a **growing metal stock**. This stock could be a strategic reserve of base metals and critical raw materials. From this perspective supporting the development of climate friendly technologies by investing in improved and cost-efficient techniques will enhance the recovery of metals and alloys from secondary raw material streams. At the same time harmonization of the wastes and products policies, as well as national and local implementing rules, is imperative. The hurdle of administration of cross border wastes or by-products transport must be overcome in order to develop sustainability in the context of circular solutions. Finally, for this circularity it is important the recognition that metals production forms an eco-system with strong technical and economic interlinkages between primary and secondary production (**industrial symbiosis**) and foremost the role of carrier metals to enable the production and recovery of other metals or even precious or rare metals.

Last but equally important is the **investment in innovation**. The EU should support the industry in making steps to reduce its carbon footprint. Non-ferrous metal industry has the potential to further



innovate its production process, however, this step requires high risk and capital investments. The industry will have to both engage in projects (e.g. Horizon Europe) that can serve multiple metals production routes and in cooperation with other industries (e.g. on CC(U)S and Hydrogen) through industrial partnerships. Regarding the industrial process innovation, it will be important for companies to have a smooth and reliable **innovation support process** from basic R&D to commercialization over different innovation support instruments.

Overall, it is beyond doubt that the transition to a decarbonised future will require large upfront capital investments and a central strategic plan for the non-ferrous metal sector in order to maintain Europe as a global leader not only at the economic level, but also at the level of environmental and social protection policies, by setting a successful example at home.

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for Energy Intensive Industries

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D3.1 - EIIs Sector Status in Europe

Steel industry

Author: Irene Bolea, Clara Jarauta, Alessandro Carmona

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Abbreviations

Abbreviation	Definition
BAT	Best Available Technologies
BF	Blast Furnace
BF-BOF	Blast furnace-basic oxygen furnace
BOF	Basic Oxygen Furnace
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
COG	Coke oven gas
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
DRI-EAF	Direct reduced iron-electric arc furnace
EAF	Electric Arc Furnaces
EII	Energy Intensive Industry
EOR	Enhanced oil recovery
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gases
NG	Natural gas
OHF	Open hearth furnace
SRF	Solid recovered fuels
TRL	Technology Readiness Level



1 Introduction and objectives

The present report constitutes part of Deliverable 3.1 - EIIs Sector Status in Europe, focusing on the **Steel sector**. The report aims to capture the current status of the steel sector in Europe, provide information regarding its energy and GHG emissions profile and outline different alternatives that are being investigated for their decarbonisation.

The European sector is under pressure due to its CO_2 emissions produced by its high energy and resource intensive processes. In 2018, the European Commission made public its long-term strategy on climate protection to make it a region by 2050 free of the emissions of green-house gases. The sector of conventional steel production in Europe is one of the biggest sources of CO_2 emissions. The sector contributes to approximately 4% of total European CO_2 emissions. Regarding the industrial sector, steel making process in Europe contribute with 22% of CO_2 emissions [1].

Steel in Europe is mainly produced by two routes Figure 1. The primary route involves the processing of iron ore to produce iron sinter or pellets, and the melting these in a blast furnace (BF) with coke to make pig iron. This is processed in a basic oxygen furnace (BOF) to create steel. The rest of the steel produced in Europe comes from the secondary route where steel is produced from scrap metal by heating it in an electric arc furnace (EAF).

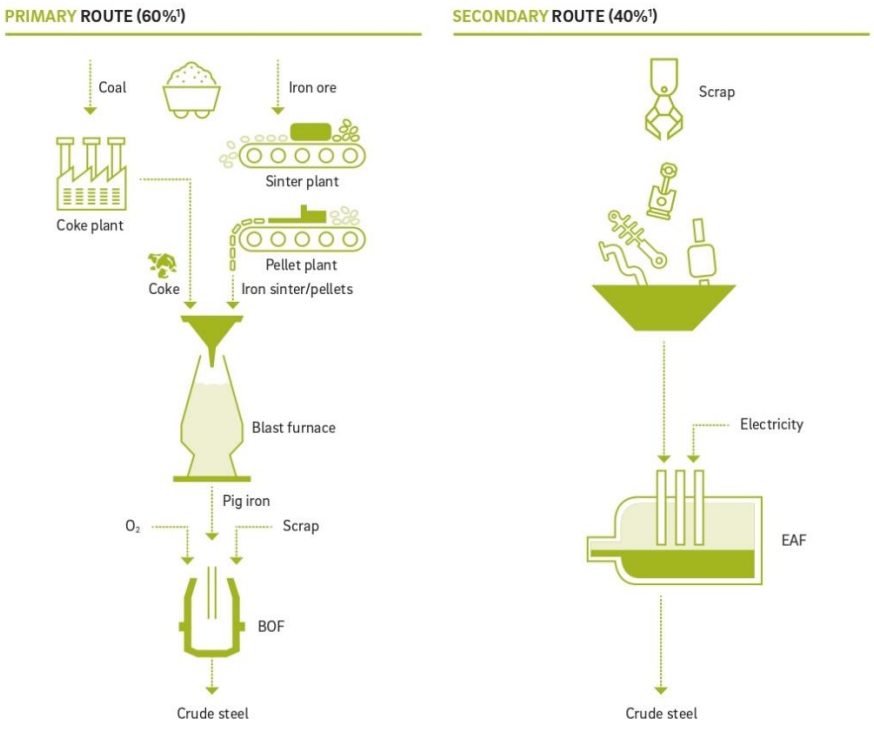


Figure 1 – Primary and secondary routes for the production of European steel.

While the primary route emits mainly direct greenhouse gases, the secondary route emits mainly indirect greenhouse gases, which depend on the electricity mix used in the EAF. In consequence, the primary route is the main target to reduce emissions in the sector.

Table 1 - Overall measures for the decarbonization of the steel sector processes.

Primary route	Secondary route
• Methods such as coke dry quenching and optimizing pellet ratios, as well as Blast Furnace (BF) equipment like top gas recovery turbines • Replacing coke with natural gas can also significantly cut CO_2 in primary steel making • Injecting hydrogen or ammonia into the BF to partly replace pulverized coal	• Making savings on the electricity used to power the Electric Arc Furnace (EAF) • Shifting the electricity mix towards renewables

Following this introduction, Chapter 2 gives a general overview of the steel sector and its importance for the European and global economy. Chapter 2 englobes the main industrial activities in the steel industry, concerning production as well as the highest overall energy consumption activities. The report provides information on the current usage and importance, main production processes, energy and GHG emission profile, as well as potential alternatives for cleaner production processes for mitigating their climate impact.



2 Steel

At around 1.9 billion tonnes of production per year (EU: 139 million tonnes), steel is the third most abundant man-made bulk material on earth, after cement and timber. Its use is ubiquitous, with the material serving as a key input to the buildings, infrastructure, transport, machinery and consumer goods sectors [2]. While other materials provide alternatives to steel in several applications, its high strength, recyclability and durability, the ease with which it can be used to manufacture goods, and its relatively low cost make its wholesale substitution unlikely in the foreseeable future [3].

The iron and steel sector directly employs around 6 million people and generates around USD 2.5 trillion in revenue globally. The steel industry forms the lifeblood of many local economies, but at the same time steel is one of the most widely traded commodities in the world, with producers competing in an international market [3].

Steel needs energy and the energy system needs steel. Iron and steel production is a highly energy-intensive industrial activity, with the sector accounting for 20% of industrial final energy consumption and around 8% of total final energy consumption. Steel demand is projected to grow in net terms even as the stock of steel in advanced economies saturates, to support a growing population and rising levels of economic welfare, particularly in emerging economies. Steel is also a critical input for the clean energy transition. The generation and use of electricity depend in part on the ferromagnetic properties of steel and its alloys. Steel is a key input material for wind turbines, transmission and distribution infrastructure, hydropower and nuclear power plants, among other critical energy sector assets [3].

While being a facilitator of the clean energy transition, steel is also a large contributor to the current challenge we face in meeting our climate goals: direct CO_2 emissions from the sector are around 2.6 Gt CO_2/ a or around a quarter of industrial CO_2 emissions, owing to its large dependence on coal and coke as fuels and reduction agents. This is equivalent to about 7% of total emissions from the energy system, when including industrial process emissions. A further 1.1 Gt CO_2 of emissions are attributable to the use of its off-gases, 5 along with other fuels, to generate the electricity and imported heat it consumes [3].

Urbanization, modern city lifestyle, skyscrapers, and even wind turbines need more steel than in the past. Steel products are durable. They have a relatively long lifetime relative to other consumer goods. We may wait a hundred years or more to recycle or replace the steel in buildings, bridges, and infrastructure. Figure 2 well describes the predominance of long service life steel products in modern societies. Only some metal products for daily life, such as steel cans and iron bars, have



short service life. Thus, recycling, replacement, and secondary steel naturally have a time lag and hence are limited in their ability to serve as decarbonization options, although they have significant overall potential [4].

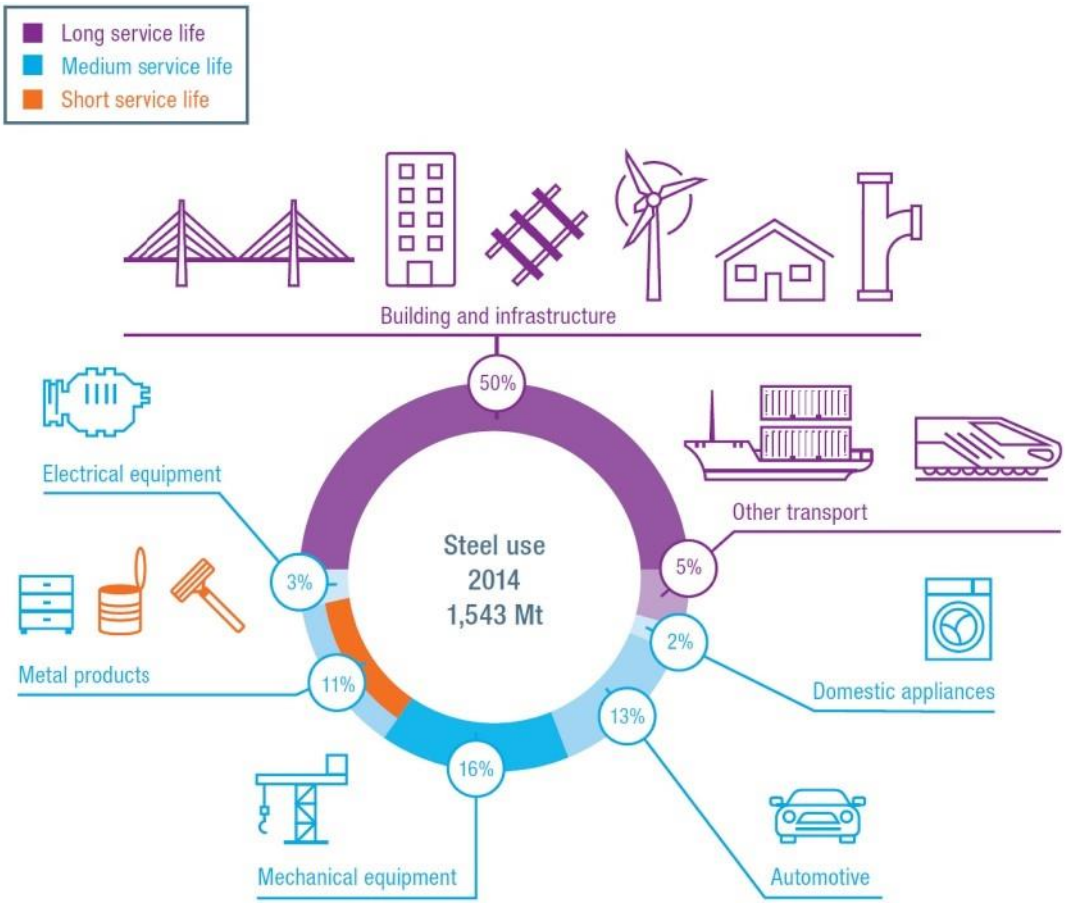


Figure 2 – Steel products and durability. Source: [4].

2.1 Main steel products and companies

“Iron” denotes the chemical element in its pure form, but also carbon-saturated intermediate (e.g. “pig iron”) and final (e.g. “cast iron”) products in the iron and steel sector. “Steel” denotes an alloy of iron and carbon, of which “carbon steel” is the simplest and most common variety. Many other elements are added to form more complex steel alloys, augmenting or diminishing certain physical properties for a given application. Chromium or nickel are added to form “stainless steel”, known for its ability to withstand corrosion, commonly being used for kitchenware. Molybdenum, vanadium, manganese, tungsten and titanium are further examples of alloying elements used to garner or enhance a variety of desirable properties. There are around 3500 different grades of steel in use

today, many of which have been developed in the past 20 years [3]. Table 2 shows the four types of steel.

Table 2 - Grades of steel. Source: [5].

Grade of steel	Description
Carbon steels	• Carbon steels only contain trace amounts of elements besides carbon and iron. This group is the most popular of the four grades of steel and it accounts for 90% of steel production. • Carbon Steel has three main subgroups depending on how much carbon is in the metal: Low Carbon Steels/Mild Steels (up to 0.3% carbon), Medium Carbon Steels (0.3–0.6% carbon), and High Carbon Steels (more than 0.6% carbon). • Companies often manufacture these steels in massive quantities since they're cheap to manufacture and they're strong enough to use in large-scale construction.
Alloy steels	• Alloy steels are created by adding additional alloying elements like nickel, copper, chromium, and/or aluminium. • Incorporating these elements enhances the steel's strength, ductility, corrosion resistance, and machinability.
Stainless steels	• Stainless steels contain 10-20% chromium as their alloying element, as well as other elements such as nickel, silicon, manganese, and carbon. • These steels have remarkably high corrosion resistance and are safe to use in outside construction because they have an increased ability to withstand rough weather. • They are also widely utilized in electrical equipment. 304 Stainless Steel, for example, is highly sought after for its ability to withstand the elements while keeping electrical material out of harm's way. • While different grades of stainless steel like 304 Stainless Steel have a place in construction, a majority of industries use stainless steel for their sanitary properties. These steels are commonplace in medical equipment, piping, cutting tools, and food processing equipment.
Tool steels	• Tool steels, excel in cutting and drilling equipment. The secret is the tungsten, molybdenum, cobalt, and vanadium that increases their heat



	resistance and overall durability. And since they retain their shape under heavy usage, they're the go-to material for most hand tools.

Small adjustments to the amount of carbon contained in steel can have a marked impact on its properties. While steel can contain up to around 2% carbon by weight, this is quite rare, with the majority of carbon steels containing less than 0.25% carbon. Raising the carbon content of steel has the impact of increasing its hardness (this can be thought of as the ability to scratch it), but also its brittleness (this can be thought of as the tendency for the material to fracture, rather than bend, when under stress). High-carbon steels are typically used for applications where resistance to abrasion is required – an important example is the steel used to make tools (Table 2). The property of steel that is more commonly sought is ductility – the opposite property of brittleness. The ability of steel to deform both elastically (whereby the original shape is returned to instantaneously) and plastically (whereby the shape is permanently altered), without breaking, makes it the natural choice for many structural applications, such as beams and columns for buildings, and chassis for vehicles [3].

While steel is used as the primary material in many applications, it is also paired with a wide variety of other “partner” materials and coatings. Reinforced concrete is an important example in the buildings and infrastructure demand segments. Steel has high tensile (pulling) strength. Concrete has low tensile strength, but relatively high compressive (pushing) strength. Concrete reinforced with steel, either in a prefabricated element, or cast in situ on a building site, is a ubiquitous composite engineering material used for foundations, floor slabs and shear walls. One potential weakness of steel as a material is its tendency to corrode, particularly in the presence of moisture and oxygen. To avoid this, steel can be coated with protective paint or bathed in molten zinc (a process called galvanising) so that it can be used in applications where exposure is unavoidable, such as the hulls of ships or the shafts of wind turbines. Steel also loses its strength when heated to very high temperatures. In structural applications steel can be coated with a protective layer of another material (such as plasterboard or intumescent paint), or oversized to allow for a degree of lost strength in a fire [3].

Liquid steel is commonly continuously cast into slabs (semi-finished steel products cut into various lengths, flat products), billets (semi-finished steel products with a square cross section up to 155 mm × 155 mm), and blooms (semi-finished steel products with a square cross section above 155 mm × 155 mm). These semi-finished products may be transported to other sites for further processing, or converted to finished steel products in processing plants, often in a separate facility or company (Figure 3). Conversion to finished products can involve various processes such as rolling, forming, pressing, cutting and bending, with some finished products requiring more steps than others (for



example, successive rounds of rolling—hot and cold—and coating). Key finished products include coil, sheets, strips, wire, bars, rods, tubes, pipes, rail and plated/coated versions of each of these products [4].

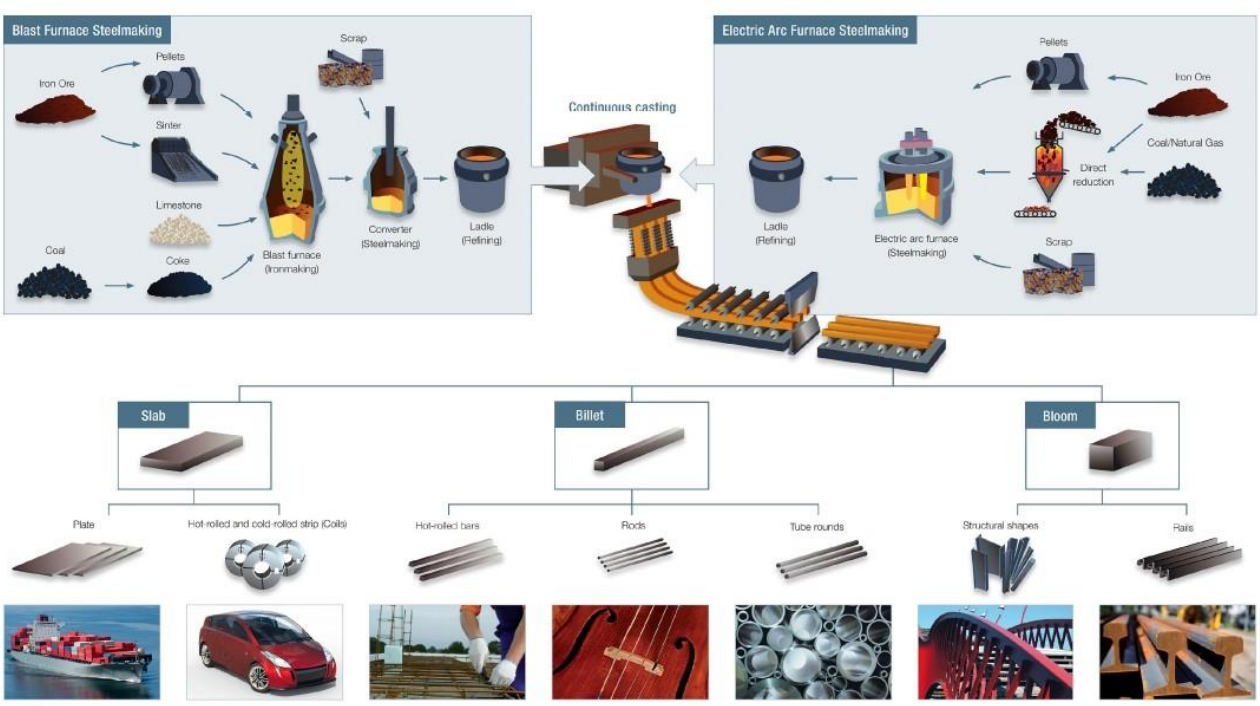


Figure 3 – Mains steel routes and finished products. Source: [4].

In order to be steel to be so widely used and versatile as a material, it has to be produced in a variety of forms (Figure 4). “Crude steel” is the name given to steel in its first solid form, when it is cast after leaving the final furnace in a given production process. While it is possible for steel to be cast directly into its final shape, this process is only used for specialised products that would be technically challenging or more costly to fabricate from off-the-shelf steel products. Liquid steel is most commonly continuously cast into slabs (flat, thick panels), billets (long rectangular beams, up to 155 millimetres [mm] by 155 mm), and blooms (long rectangular beams, greater than 155 mm by 155 mm). Much less commonly, liquid steel is cast into ingots, which are later rolled into semi-finished or finished products. These semi-finished products may be transported to other sites for further processing, or converted to finished steel products in processing plants, often in a separate facility or company. Conversion to finished products can involve various processes such as rolling, forming, pressing, cutting and bending, with some finished products requiring more steps than others (for example, successive rounds of rolling – hot and cold – and coating). Key finished products include coil, sheets, strips, wire, bars, rods, tubes, pipes, rail and plated/coated versions of each of these products.

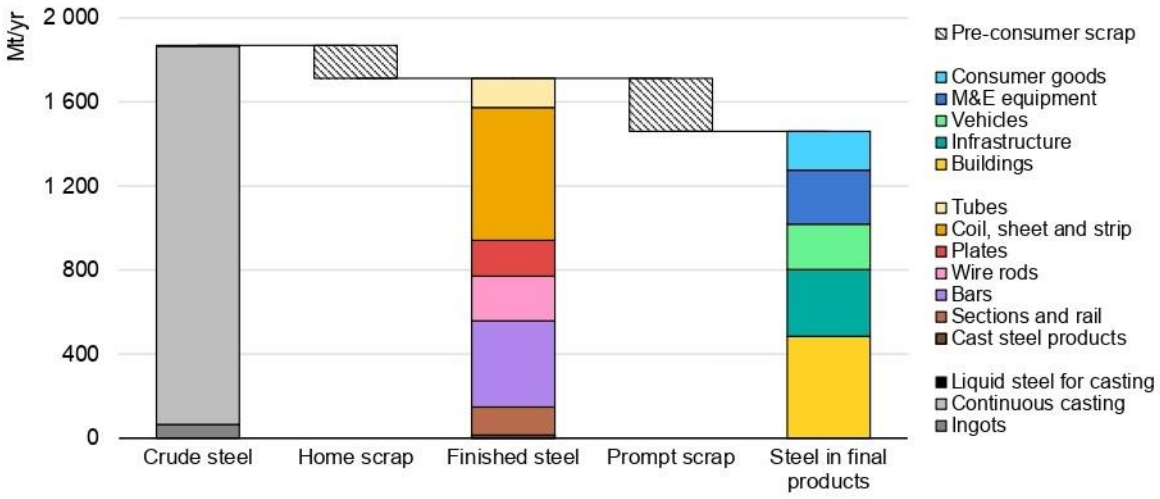


Figure 4 – Global steel production by product and demand segment in 2019. Source: [3].

Table 3 -Europe Steel Factories. Source: [6].

Company	Steel production, processing and fabrication.
Ancofer Waldram	Stocks over 20.000 tons of heavy carbon steel plates and offers rolling mills and carbon steel plates.
Ancon	Designs and manufactures steel products for the construction industry.
ArcelorMittal	Brings together the world's leading steel companies, Mittal Steel and Arcelor.
BÖHLER Edelstahl GmbH	Manufacturers of high speed steels, tool steels and special materials.
BE Group Oy Ab	A merchant in Europe within steel and metals.
Brown McFarlane	Stocks a range of carbon steel boiler plates and pressure vessel steel plate.
Celsa	Offers Corrugated B 500 SD and B 400 SD steel rolls and rods; UPN, IPN, HEB, HEA and IPE sections and rolled wire.
Covis	Specializes in supplying a full range of steel products.
CSK Steel	Operates in the design, manufacture and mounting of steel construction for the needs of building.
Diler Holding	The Company produces steel billets ranging from 100/100 mm to 180 X 180 mm.

DSD Steel	Erects and produces steel structures for plant maintenance and industrial installation.
Euro-Mit Staal B.V	A steel processing service center specializing in slitting thin gauge material such as electrical steel, motor lamination, etc.
Fiav	Specialised in the production of special drawn steel profiles.
FOC	Starting with raw metal, the company produces rings, forged and drop forged pieces of steel ready for assembly.
Gruppo Lucefin	European manufacturer of cold-drawn steel in different sections, sizes and qualities.
Hi-Tech Steel Services Ltd	Offers main stock items and other specialist items including selected grades of stainless steel, tri-clear and tri-zin.
Huta Pokoj SA	Produces hot rolled plates, hot rolled sections, steel constructions and strips in coils.
Kind &Co	Offers tool steels from hot-forming and cold-forming tool steels to the high-alloyed special compositions.
Levypyora Oy	Offers a production programme including different kinds of cold formed steel manufactured components.
Lohmann	A manufacture of high-speed steels, tool steels, and special steels as well as wear-resistant specialty steels and heat-resistant castings.
LTC	Specialised in processing grain oriented electrical steel, high permeability and laser treated electrical steel.
Megasteel	A company specialised in the production of steel for construction.
Metal Goods	Specialised in the production of semi-finished, structural steel, stainless steel, super alloy and special alloy products.
Ovako	Ovako - Offers a production that covers low alloy steels and carbon steels in the form of bars, wire rod, tubes and rings.
Pipe and Tube Group	UK based carbon and stainless steel stockholders, developing the stock and range of services needed.
Polarputki	Produces seamless steel tubes, round bars and solid fuels.
Rostfrei Stahl	Offers sheet metal blanks, stainless steel blanks, plasma blanks, water-jet cutting, belt grinding and plasma cutting.
SCHMOLZ +	Supplier of special solutions in high quality steels.

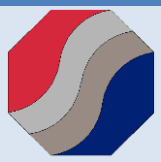


BICKENBACH AG	
SeverStal	Specialis in the steel and mining industry.
Steelgroup	Offers patented, galvanized and phosphated steel wire.
Tata Steel Europe	Producer of electrical steel, such as grain oriented electrical steel, non-oriented electrical steel and transformer cores.
Terg	Prefabricates and installs different kinds of steel construction.
Uddeholm	Offers tool steel, HPS material, finemachined products and precision strip steel.
UK Steel	Steel companies produce steel in a variety of different shapes, sizes and qualities.
Van Merksteijn	A manufacturer of steel mesh reinforcement, wire products and fencing.
Voestalpine	An European processing group with steelmaking facilities and headquarters in Austria.
Walter Watson	Operates in four market sectors: structural steel, cranes and hoists, rebar and steel stockholding.
Welser Profile	Manufacturer of special sections, tubes, components and complete profile systems made of steel and non-ferrous metals.
Zozetto	Specialised in the production of special steels: steel rolls and bars suitable for all mechanical purposes.

2.2 Steel associations

Table 4 shows the main EU steel associations and the goods they produce.

Table 4 - Steel sectors and their respective associations.

	Association
	**British Stainless Steel Association** Promotes and develops the use of stainless steel by U.K. manufacturers and end users.
	Make UK (**EEF Association)** A steel trade association for the European and UK steel industry. Formerly known

MAKE uk The Manufacturers' Organisation	as EEF, Make UK champions engineering & manufacturing in the UK, supporting businesses around the country
ACCIAIO INOSSIDABILE	**Centro Inox** Is an Italian steel association that helps in the promotion of stainless steel from Italy to the rest of the world
EUROFER THE EUROPEAN STEEL ASSOCIATION	**Eurofer** European Confederation of Iron and Steel Industries; founded in 1976, its offices are located in Brussels
IMnI International Manganese Institute	**International Manganese Institute** Industry association that represents manganese ore and alloy producers, manufacturers of manganese-based products
worldstainless	**International Stainless Steel Forum** Research organisation, which serves as the world forum on various aspects of the international stainless steel industry
	EUROMETAL The Voice of European Steel, Tubes and Metal Distribution representing all types of Steel Intermediation

2.3 Overview of the European Steel sector

In 2020, the steel sector in Europe reported that the industry supports over 2.6 million total full time equivalent jobs. From these, 722,000 were induced (27.1%), 1,620,000 were indirect (60.7%) and 326,000 direct (12.2%). The EU industry creates roughly €132 billion of gross value added (Figure 5). Indirect refers to jobs in the steel industry's EU-based supply chain. Induced refers to jobs supported by money spent by indirect and direct employees of the EU's steel industry and supply chain [7].

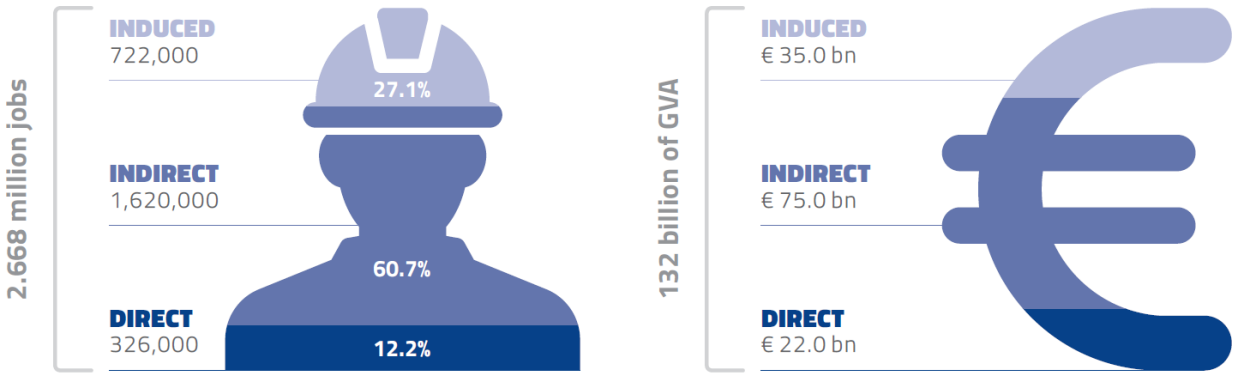


Figure 5 – Employment and gross value added in the EU steel industry. Source: [2].

The six countries that employ the highest amount of people in the European steel sector are Germany (83,200), Italy (30,389), France (26,500), Poland (24,000), Romania (22,000) and Spain (17,150) [2]. The evolution of the employment in the EU steel sector has experienced a reduction in the number of employed people in the sector since 2011. The sector has also seen a slight increase from 2016 up to 2019. The European Steel Association has reported a decrease of 8% in employment from 2011 when the number of employed people went from 365,610 to 326,462 in 2020 [2]. The gross value added by the sector is shown in Figure 6. The steel sector is the third most important industrial sector in Europe according to EUROFER [2].

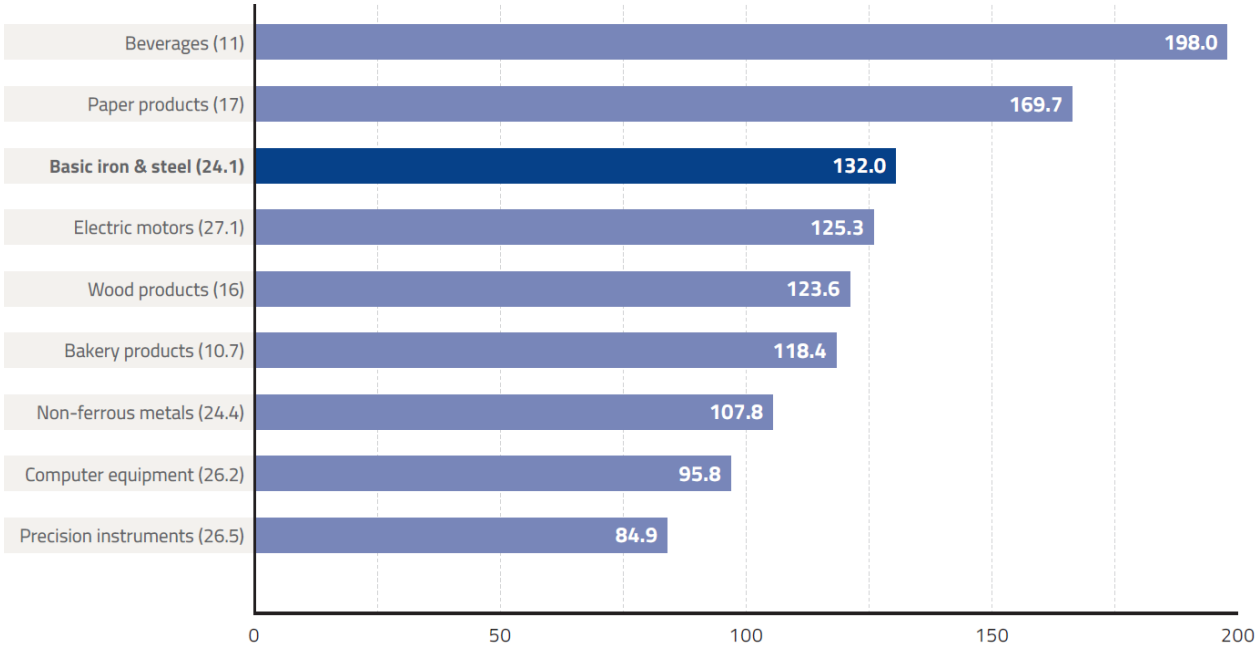


Figure 6 – Value of production compared with other EU industries in € million. Source: [2].

World crude steel production is dominated by Asia with a total share of around 74%, of which China has a share of 58% (Figure 7). Europe is the second region with the highest total share of more than 15%, of which the European Union has 7.6%. North and South America combined report a total worldwide share of 7.6%, of which the United Stated has a share of 4%. In Australia and New Zealand, the production of crude steel is minimal with a total share of only 0.3%. The crude steel production in the EU is shown in Figure 8. As expected per the employment shown above, Germany has the highest share of crude steel production with a 25.6%. The rest of counties with a share higher than 5% are Italy (14.6%), France (8.3%), Spain (8.0%), Poland (5.6%) and UK (5.1%).

	2020	% shares 2020
Asia	**1,351.3**	**73.9%**
of which China	1,054.7	57.7%
of which India	100.3	5.5%
of which Japan	83.2	4.6%
Europe	**278.1**	**15.2%**
of which European Union	139.3	7.6%
of which CIS	100	5.5%
North America	**101**	**5.5%**
of which United States	72.7	4.0%
South America	**38.2**	**2.1%**
Middle East	**40.7**	**2.2%**
Africa	**12.6**	**0.7%**
Australia/New Zealand	**6.1**	**0.3%**
WORLD	1,828.2	100%

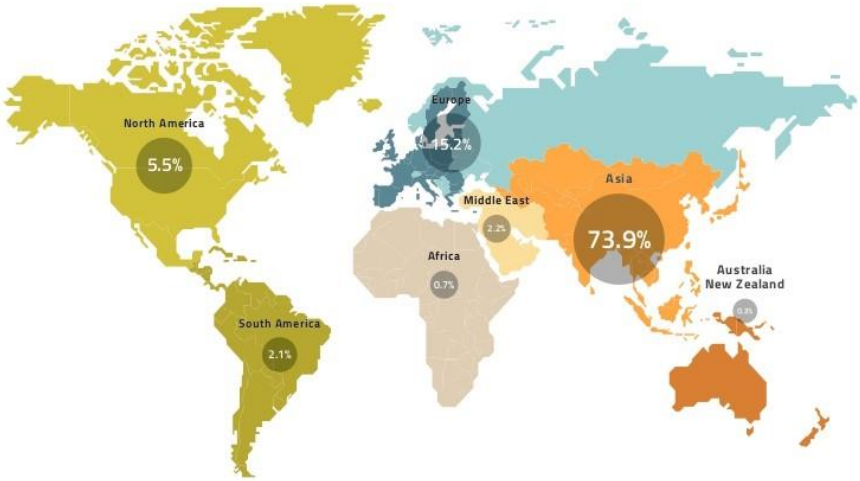


Figure 7 – Worldwide crude steel production per region in thousands metric tonnes. Source: [2].

SOURCE: EUROFER

		2020	% shares 2020
1	GERMANY	35,658	25.6%
2	ITALY	20,379	14.6%
3	FRANCE	11,596	8.3%
4	SPAIN	11,142	8.0%
5	POLAND	7,856	5.6%
6	UNITED KINGDOM	7,099	5.1%
7	AUSTRIA	6,765	4.9%
8	BELGIUM	6,119	4.4%
9	NETHERLANDS	6,054	4.3%
10	CZECH REPUBLIC	4,450	3.2%
11	SWEDEN	4,383	3.1%
12	FINLAND	3,498	2.5%
13	SLOVAKIA	3,444	2.5%
14	ROMANIA	2,790	2.0%
15	OTHERS	2,203	1.6%
16	LUXEMBOURG	1,886	1.4%
17	HUNGARY	1,513	1.1%
18	GREECE	1,308	0.9%
19	SLOVENIA	623	0.4%
20	BULGARIA	484	0.3%
21	CROATIA	45	0.0%
	TOTAL	139,295	100%

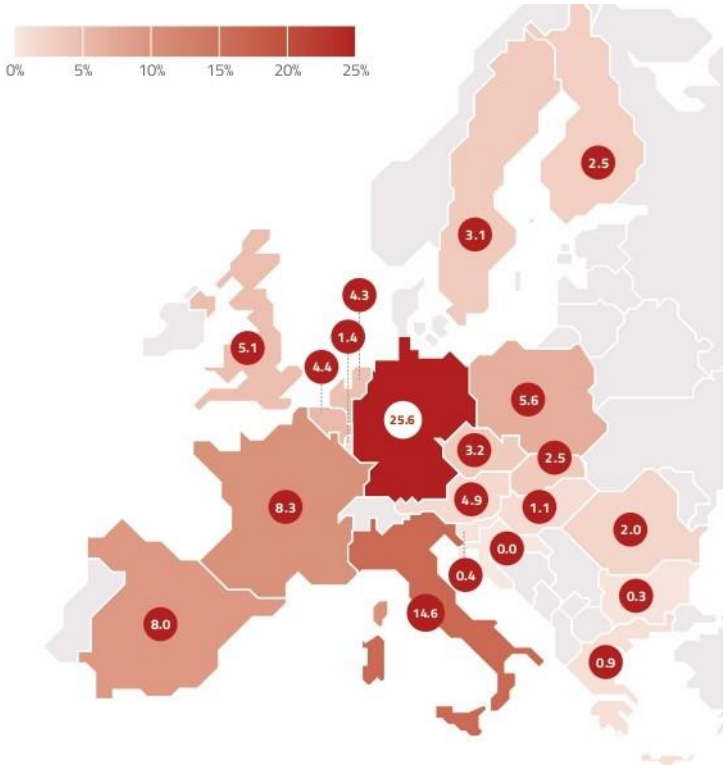


Figure 8 - Crude steel production per country in the EU by relative size in thousands metric tonnes. Source: [2].

Regarding the route to produce steel, the main route is the Basic Oxygen Furnace as seen in Figure 9 (left). By quality carbon steel non alloy is the predominant form of steel in the EU (Figure 9 - right).

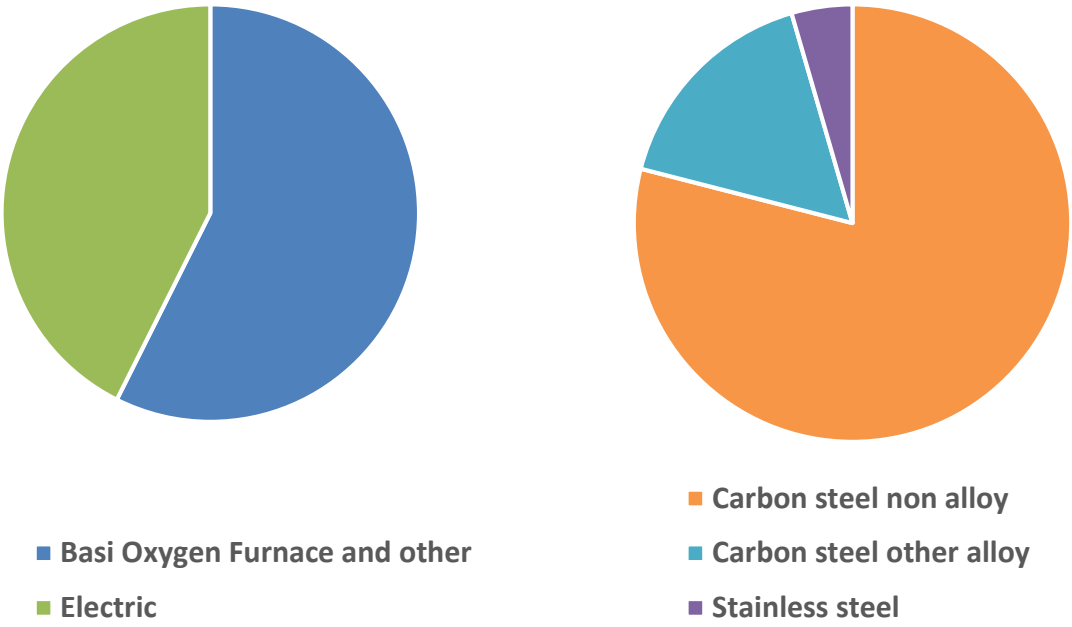


Figure 9 - Crude steel output by product route (left) and EU crude steel production by quality (right). Source: [2].

Figure 10 shows the EU total finished steel production by product in 2020. Downstream processing converts some hot rolled wide strip into cold rolled flat, and some cold rolled flat into hot dipped and some hot dipped into organic coated. Downstream processing uses both domestic and imported steel. Production totals are thus not add up precisely.

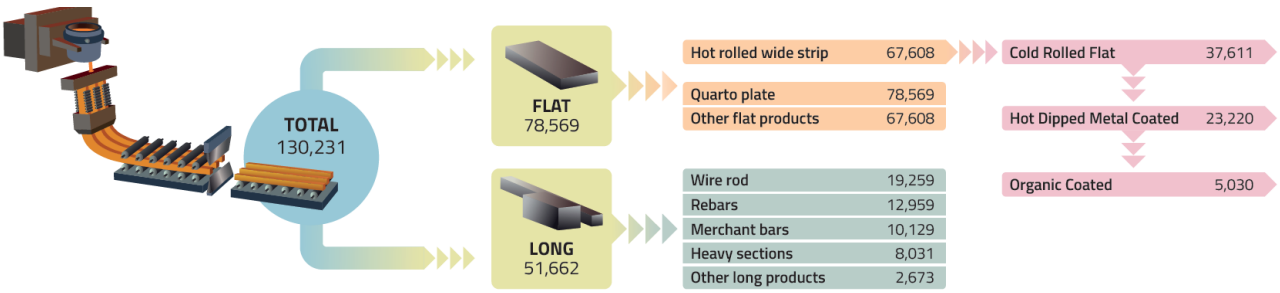


Figure 10 – EU total finished production by product. Source: [2].

Figure 11 shows the map of steel production in Europe. In the map, both routes of steel production can be distinguished: i) Blast furnace/Basic oxygen furnace and ii) Electric arc furnace. Two routes depending of different feedstocks as described earlier (Figure 1).

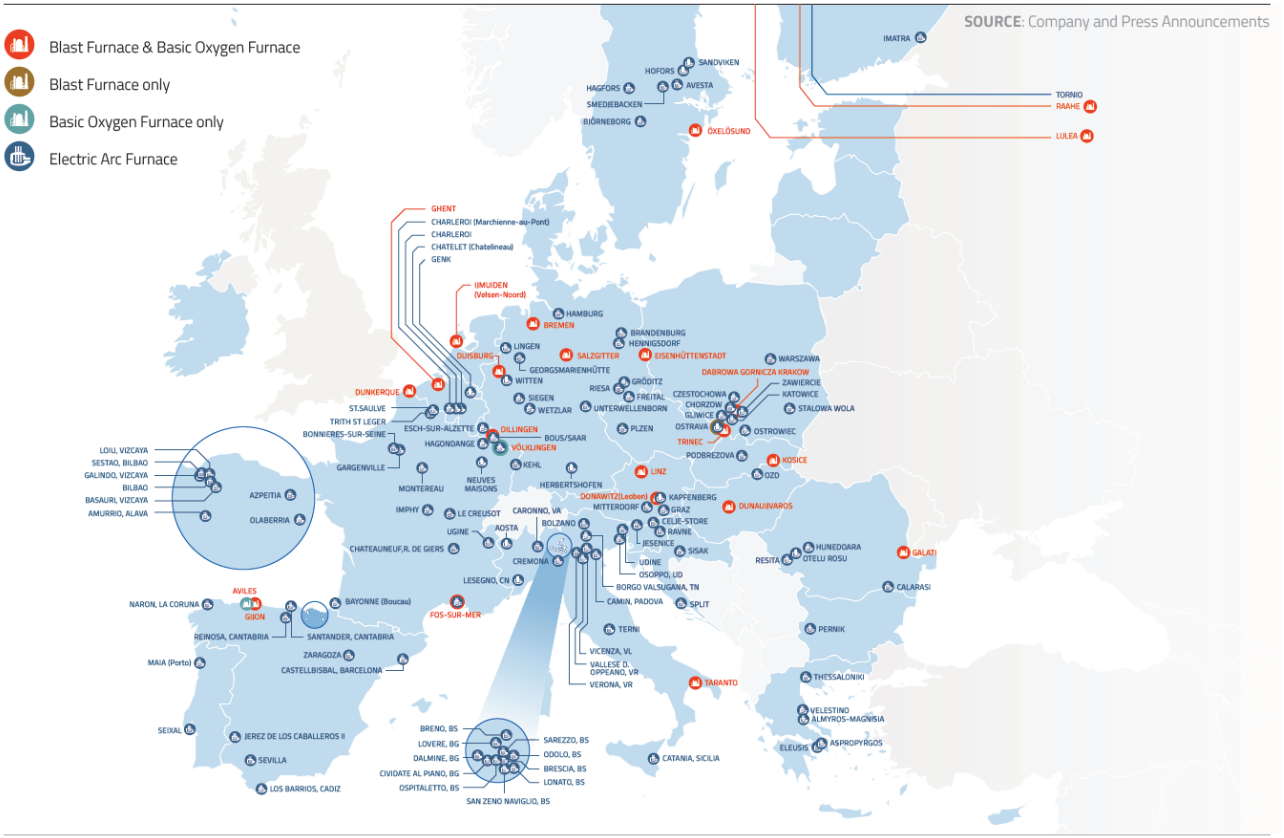


Figure 11 – Map of steel production in Europe. Source: [2].

2.4 Steel main applications

Figure 12 shows the steel consumption per steel-using sector. As expected, the Construction sector is the one with the highest consumption of steel among the different sectors (38%). The second highest consumer is the automotive sector with 16%.

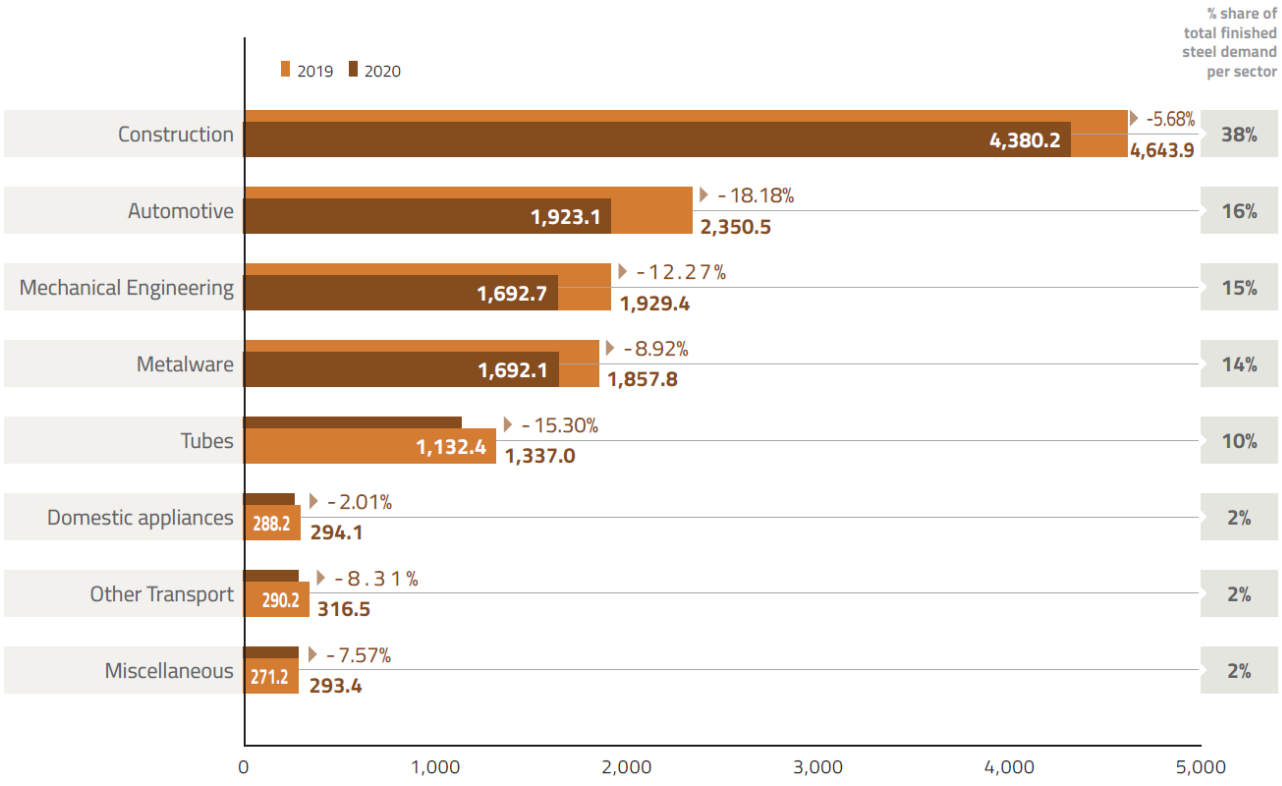


Figure 12 – Steel consumption per steel consumption sector. Source: [2].

2.5 Production process

Figure 13 shows the main current steel production pathways and material flows. The main outputs to steel production today are:

- Iron ore;
- Energy (main coal, natural gas and electricity);
- Limestone and;
- Steel scrap.

Iron ore and scrap are used to provide the metallic charge. Scrap provides a significantly higher metallic charge concentration (>95%) than iron ore (50-70%). Metallic input of 1.05 to 1.20 tonnes is required per tonne of steel [3]. Energy is used in the steel-making process as heat to melt either the steel scrap or in the case of the iron ore input to chemically reduce, i.e., remove oxygen from its naturally occurring states found in the earth's crust (

Table 5).

Table 5 - Key iron ore constituents. Source: [3].

Compound name	Formula	Iron content (%)
Magnetite	**Fe3O4**	**72.4**
Haematite	**Fe2O3**	**69.9**
Goethite	**FeO(OH)**	**62.9**
Limonite	**FeO(OH)•n(H2O)**	**55.0**
Siderite	**FeCO3**	**48.2**

As previously indicated in Section, primary steel production refers to the process that uses iron ore as its main source of metallic input. Secondary production is based on scrap (Figure 13). It is worth noting that the distinction between primary and secondary steel production is nowadays less clear since scrap is often used in the primary route as well and iron ore can be used in electric furnaces. When describing the steel making process in a specific region/plant, it is highly advisable to mention the share of scrap in total metallic inputs alongside the shares of primary and secondary production.

CO_2 and H_2 are the reducing agents to cleave O2 from iron ore-containing compounds (

Table 5). It is well known that as per today, all CO_2 and H_2 used to reduce iron ore are generated from fossil fuels, mainly coal and its derivative coke, and to a lesser proportion natural gas. Lime flux in the form of limestone and dolomite are used at various stages of the steel making process to help remove purities such as sulphur, phosphorus and silica. The production and use of lime (in its several forms) leads to the emissions of CO_2, and when chemically combines with the non-iron content of the iron ore input, they form a steelmaking co-product called slag [3].

As a rough estimation, 1 tonne of steel results in around 400 kg of slag, around 125 kg of which stems from the basic oxygen furnace and the rest from the blast furnace [3]. Slag is also produced in electric furnaces fed by scrap, at around half of the rate and with a different chemical composition. Unless slag can be put to use elsewhere, it has to be stored or disposed of, but this is costly and can create a safety hazard (see Section 2.7.1).

The primary production of crude steel has three key phases:

- Raw material preparation;
- Ironmaking; and



- Steelmaking.

After mining and beneficiation, the iron ore inputs need to be processed before they are used in the ironmaking step. Unprocessed iron ore is found in a mixture of fines and lumps, with highly concentrated forms of the latter being rarer and typically more expensive, as it can be directly used without further processing. Iron ore fines need to be agglomerated, either by producing sinter or pellets [3]. Agglomeration processes use heat and pressure to form nodules (sinter) and pebble-sized particles (pellets), which when stacked in a furnace allow gases to flow through and around them. Depending on the iron content of the ore and the pellet or sinter quality, these processes consume varying quantities of coal, coke, natural gas and electricity, but typically in the range of 1-3 gigajoule (GJ) per tonne of pellets or sinter. The quality of raw materials used has a significant impact on the energy and emission intensities of the subsequent process of steelmaking [3].

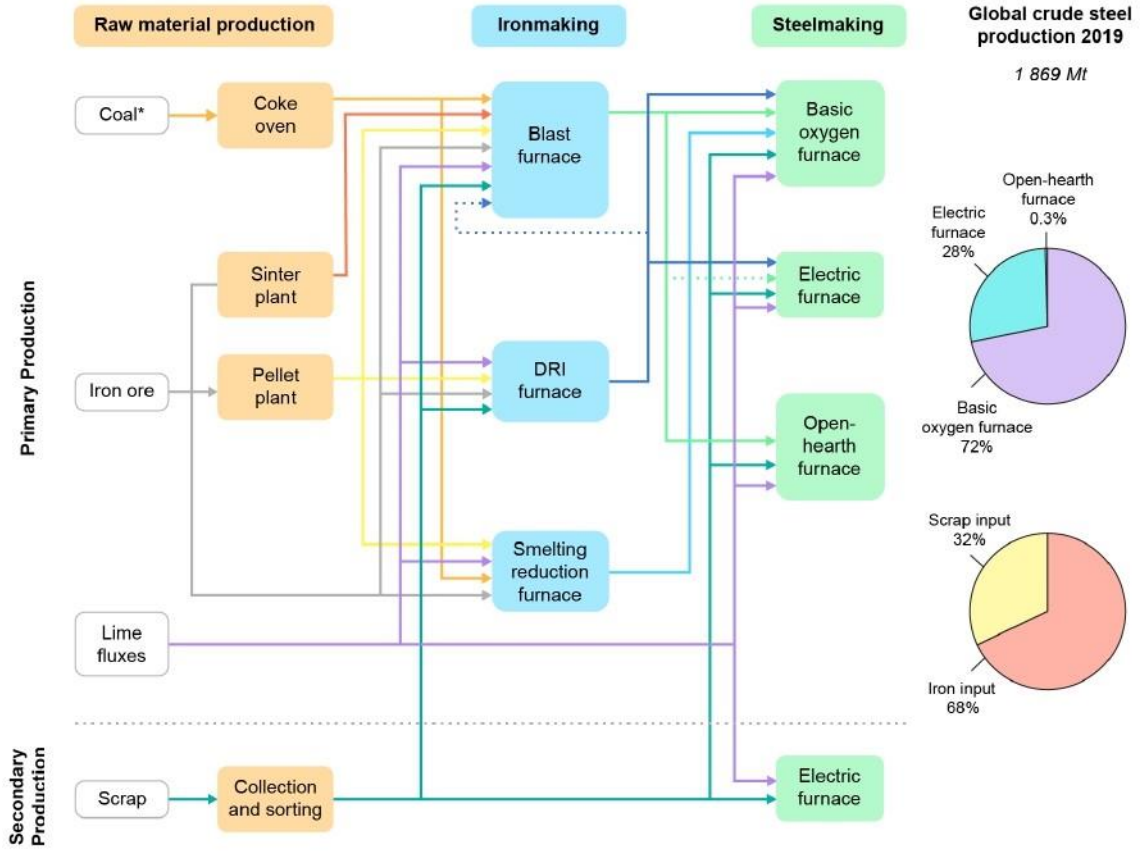


Figure 13 – Main steel production pathways and material flows in 2019. Source: [3].

Notes to Figure 13: Coal is a key material input to coke ovens for conversion into coke; while not represented here, it is also an energy input into other process units, alongside other energy inputs like natural gas and electricity. DRI: direct reduced iron; EAF: electric arc furnace. In some regions (particularly the United States), the DRIEAF route has a high ratio of scrap to DRI inputs, but is still categorised as primary production. Iron

ore includes concentrate, lump and fines. Electric furnace includes both EAFs and induction furnaces. DRI input into blast furnace and blast furnace input into EAFs are less common (dashed lines).

Coke is another input that requires an intermediate step of transformation. Coking coal (a specific grade of hard coal with elevated carbon content) is heated to around 1100ºC in a coke oven in the absence of air to remove its volatile components, resulting in coke a mostly carbon-based substance with high compressive strength. For a detailed compendium on coke characteristics and production see: [8].

Scrap also requires some degree of preparation before it is used in steelmaking (and less commonly in ironmaking), depending on where it was sourced. Post-consumer scrap (as opposed to that generated in mostly pure forms within a production site or manufacturing operation) must be separated from other materials, which is typically done with the help of magnets. Copper is a persistent contaminant. It can be difficult to separate from steel at a reasonable cost, as it is often wrapped tightly around steel in several end-use applications [3].

Whereas many – comparatively small – steel plants around the world exclusively employ the secondary route for production (i.e. purely scrap-based), primary production facilities can use up to around 15-25% scrap alongside iron ore. While iron ore is mined all over the world (it is one of the most abundant elements on earth), scrap availability is limited by the rate at which steel products reach the end of their life and the effectiveness of scrap collection and sorting systems. Around 700 Mt per year of scrap is consumed each year for steel production (compared with a total crude steel production volume of 1 869 Mt per year), with comparable amounts of scrap used in the primary and secondary routes [3].

2.5.1 Production cost

The cost of producing steel is highly dependent on the cost of the main inputs to the production processes, particularly the cost of iron ore, scrap and energy inputs. Using the simplified levelised cost metric as a proxy for the cost of producing one tonne of steel, these raw material and energy inputs typically account for 60-80% of the total (Figure 14). The annualised cost of capital expenditure (CAPEX) and the fixed operational expenditure (OPEX) account for the remainder [3].

The prices of the main metallic raw material inputs – iron ore and scrap – strongly influence the final production cost of crude steel. Scrap tends to be more expensive than iron ore, reflecting the lower conversion cost (excluding input materials) to produce steel. Iron ore prices are governed by a more straightforward set of supply and demand dynamics. The cost of producing iron ore, which is mined on a large scale in Australia, Brazil, the Russian Federation (“Russia”), China and India, is primarily



dictated by its iron concentration, local labour costs and capital costs. The demand for iron ore is dictated by the demand for steel, and when the supply of iron ore is high relative to the level of demand of steel, iron ore prices tend to be lower, and vice versa. Prices of iron ore fines in 2019 averaged around USD 90 per tonne, whereas just 4-5 years earlier they were around half this level. Like steel, iron ore is also widely traded [3].

As previously discussed, scrap availability is finite and predetermined, but there is still a cost curve associated with its collection, sorting and ultimate provision. Two key dynamics govern this cost curve. At higher absolute scrap prices, more scrap becomes available as higher separation and sorting rates become economic. A study of the US market suggests a step change in the elasticity of scrap supply once prices exceed the historically high value of USD 250-300, with considerably more scrap becoming available, reflecting the additional incentive required to motivate higher recovery rates. The price at which this incentive has an impact will vary across regions depending on overall availability, labour costs etc. In tandem, the price of scrap relative to that of iron ore also governs its demand level. Scrap demand is higher when its price relative to the cost of iron ore is low [3].

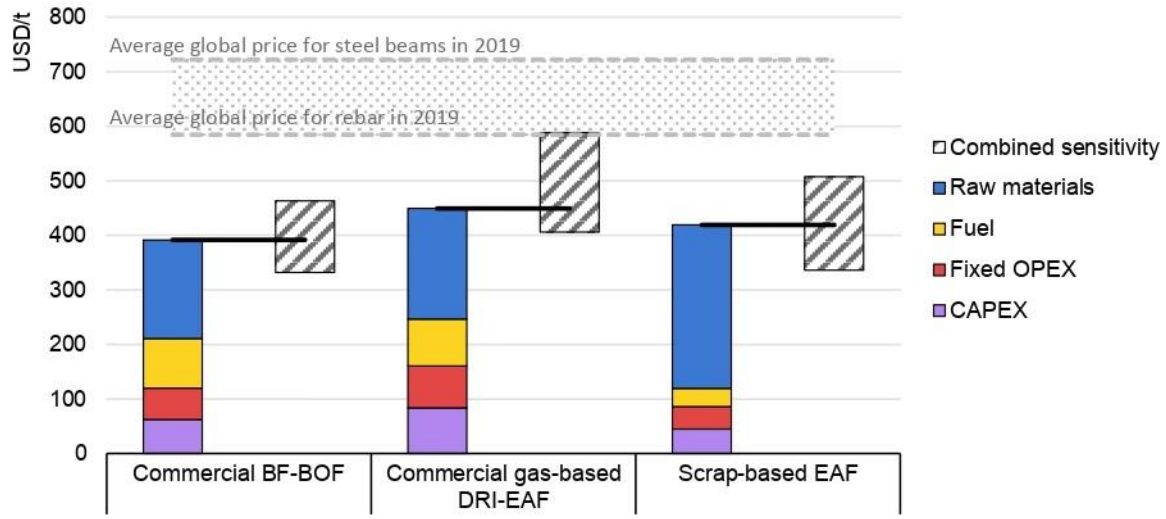


Figure 14 – Simplified levelized cost of steel production via major commercial routes. Source: [3].

Notes to Figure 14: Annualised CAPEX: USD 52-94/tonne (t) crude steel for BF-BOF, USD 53-136/t crude steel for DRI-EAF, USD 34-58/t crude steel for scrap-based EAF. CAPEX includes engineering, procurement and construction costs. 8% discount rate, 25-year lifetime and a 90% capacity factor are used for all equipment. OPEX: USD 48-87/t crude steel for BF-BOF, USD 48-125/t crude steel for DRI-EAF, USD 31-54/t crude steel for scrap-based EAF. Energy prices: Natural gas = USD 2-10/million British thermal units, thermal coal = USD 35-80/tonne of coal equivalent (tce), coking coal = USD 75-155/tce, and electricity = USD 30-90/megawatt

hour (MWh). Scrap = USD 200-300/t. Iron ore = USD 60-100/t.

2.6 Energy consumption and GHG emissions

2.6.1 Energy consumption

Table 6 shows the worldwide energy source in iron and steel making processes. In the EU (27 countries) specifically, 0.84 EJ was consumed in 2020 in several forms of energy [9].

Table 6 - Final energy use in iron and steel making in 2015. Source: [4].

Process	Energy use (EJ/year)	Share (%)
Coking coal and coke	24.1	70.0
Other coal	6.1	17.6
Blast furnace gas and coke oven gas	-3.3	-9.6
Natural gas	2.3	6.7
Oil	0.4	1.2
Biomass	0.1	0.4
Electricity	4.0	11.8
Heat	0.6	1.9
Total	**34.4**	**100.0**

Note to Table 6: Negative energy use represents recovered energy in the iron and steel making processes.

Once scrap is collected and sorted, the secondary production route mainly requires electricity to melt the steel in an electric furnace, often along with a small amount of natural gas or coal to form a protective slag foam. Highly conductive graphite electrodes are also consumed during the process of heating the scrap metal to temperatures of up to 1 800°C. **Electric arc furnaces (EAFs)** are the most commonly used furnace for scrap-based production, but typically less energy-efficient induction furnaces are also used, particularly in India and China. ***Producing one tonne of steel via the scrap-based route requires around 2 GJ of final energy per tonne of crude steel*** [3].

The primary production pathway is more complex than the secondary route, comprising multiple different process arrangements. The most common primary production pathway is the **blast furnace-basic oxygen furnace (BF-BOF) route**, which accounts for around 70% of global steel production and around 90% of primary production. Coke and iron ore are both fed into the blast furnace from the top; simultaneously, hot air and pulverised coal or natural gas (and in an experimental site in Germany also hydrogen) are injected through pipes in the side of the lower part of the furnace called tuyeres. This results in a counter-cyclical process of descending iron ore met

by rising reducing gases. ***Producing one tonne of liquid steel via the BF-BOF route requires around 15 GJ of final energy input.*** Lime fluxes and other additives are also used in the blast furnace in varying quantities to control the level of impurities and the temperature. The blast furnace produces molten iron ("hot metal") at temperatures up to 1 400-1 500°C. The hot metal is then fed to the BOF, often in conjunction with some scrap, where oxygen is injected to lower the carbon content from approximately 4-5% to the required level of carbon for the steel grade produced (typically around 0.25%) [3].

The other main method of primary steel production is the direct reduced iron-electric arc furnace (DRI-EAF) route. The principal differences between this route and the BF-BOF route are [3]:

Table 7 - Principal differences between Direct reduced iron-electric arc furnace and Blast furnace-basic oxygen furnace. Source: [3].

Direct reduced iron-electric arc furnace	Blast furnace-basic oxygen furnace
Type of iron ore: High-quality DRI pellets	Type of iron ore: This route has the flexibility to use iron ore with more impurities, and a combination of pellets, fines, sinter and lump ore
State of the material when it is reduced: Iron ore is reduced in a solid state before being melted in the EAF, often in conjunction with some scrap	State of the material when it is reduced: Iron ore is reduced in a liquid phase
Main reduction agents: Carbon and carbon monoxide	Main reduction agents: Hydrogen and carbon monoxide
Balance of energy inputs: DRI-EAF facilities today mainly use natural gas to generate the reducing syngas (carbon monoxide and hydrogen), but can also use coal	Balance of energy inputs: BF-BOF producers mainly use coke and coal, with natural gas injection being less common
Final energy requirement: Producing one tonne of steel via the DRI-EAF route requires between 18 GJ and 30 GJ of final energy, with natural gas-based production generally being more efficient than coal-based gasification arrangements	Final energy requirement: BF-BOF requires around 15 GJ of final energy



The main BF-BOF and EAF (both DRI-EAF and scrap-based EAF) routes combined account for 95% of global steel production. Three other process units are also in use today but see very limited penetration. Smelting reduction is an alternative class of processes for ironmaking that facilitates the use of iron ore fines directly (rather than agglomerated pellets and sinter) and avoids the use of a coke oven or coking coal. Several designs are currently commercially available or under development, but the process is yet to see widespread adoption within the industry. The open-hearth furnace is an outdated alternative to the BOF and has largely been phased out given its inferior energy performance. Production of steel using induction furnaces has been increasing in recent years, despite the closure of illegal units in China. Those furnaces are generally smaller than electric arc furnaces, often used to produce special alloys [3].

2.6.2 Greenhouse gases emissions

The primary sources of CO_2 emissions in the iron and steel making processes are raw materials, including cokes, and fuel combustion. Ovens, boilers, stoves, furnaces, and other miscellaneous equipment in the processes from the sintering to the final steel product manufacturing can be CO_2 emissions sources. Figure 15 depicts the profile of CO_2 emissions in a typical BF/BOF integrated steel plant. Among 1.8 t CO emissions per ton of rolled coil in a typical integrated steel plant, 1.7 t CO_2 is associated with coal use, and the remaining 0.1 t CO_2 is responsible for lime use [4].

Three reasons make the DRI carbon content critical when used in an electric arc furnace: 1) the presence of carbon is necessary to complete the metallization of the iron in the EAF, 2) carbon represents an additional source of energy in the EAF because burning the carbon by injecting oxygen reduces the electricity consumption, consequently enabling a faster melting of the charged materials, 3) carbon enables the formation of a foamy slag in the EAF [4].



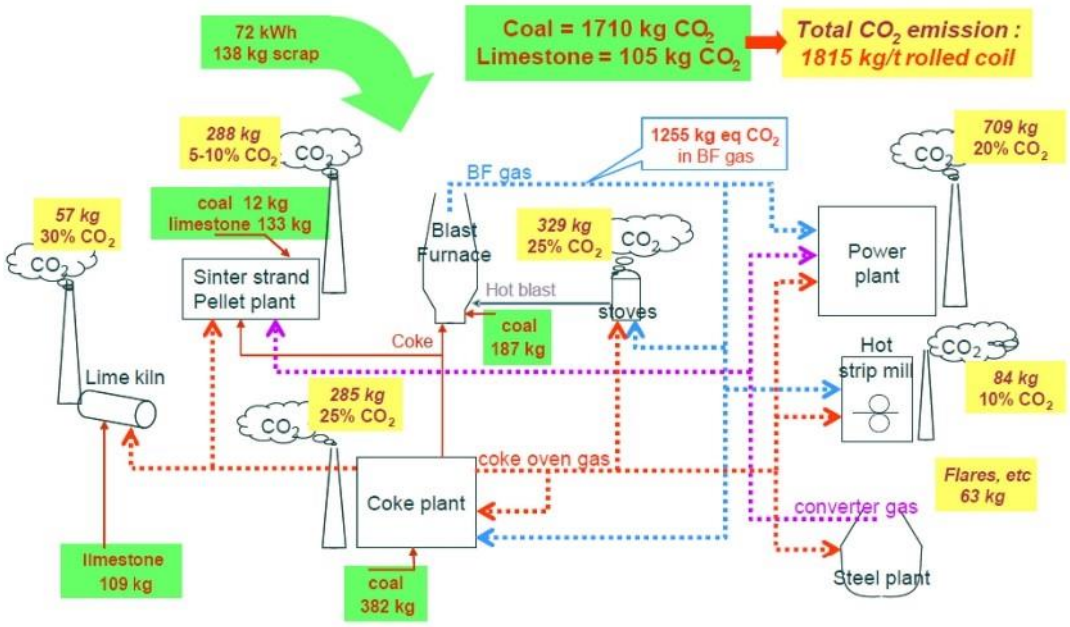


Figure 15 – CO_2 emissions from a typical steel mill. Source: [4].

The most of carbon footprints in the iron and steel industry are energy-related emissions. The IEA predicted the iron and steel industry would account for about 25–30% of direct industrial carbon emissions by 2050, even in the IEA Sustainable Development Scenario in which the GHG emissions of the iron and steel sector are reduced by 54% by 2050 (Figure 16). Asia Pacific is the key region because of this dramatic reduction of carbon emissions [4]. A study reveals direct and indirect GHG emissions in the Chinese iron and steel industry using the Material Flow Analysis. The work showed that China emitted 77.2% of GHG emissions directly in 2011, and most of them were coalfired emissions [4].

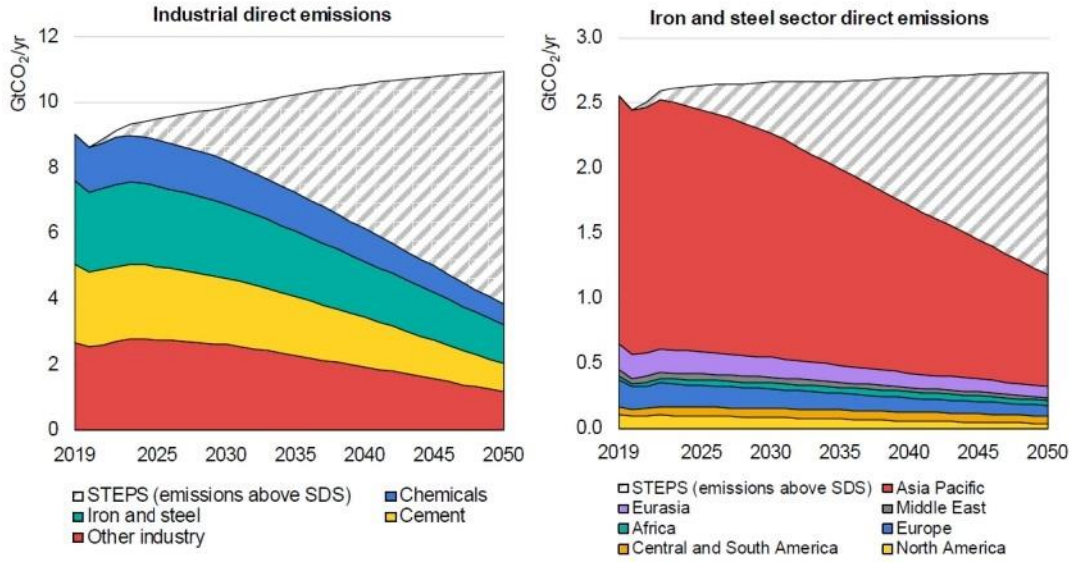


Figure 16 – The contribution of the iron and steel sector to direct industrial CO_2 emissions by scenario. Source: [4].

The European steelmaking industry emits 4% of the EU's total CO_2 emissions. It is under growing public, economic and regulatory pressure to become carbon neutral by 2050, in line with EU targets. About 60% of European steel is produced via the so-called primary route, an efficient but highly carbon-intensive production method (see Figure 1 above). The industry already uses carbon mitigation techniques, but these are insufficient to significantly reduce or eliminate carbon emissions. The development and implementation of new technologies is underway according to an analysis conducted by the German consultancy Roland Berger [1].

One alternative reduction process, H_2-based shaft furnace direct reduction, offers particular promise due to its emissions-reduction potential and state of readiness. It is the technology that the German consultancy envisages steelmakers will pursue in order to achieve carbon neutrality. H_2-based shaft furnace direct reduction is ready to use and can be introduced step-by-step into brownfield plants. This ensures operational continuity and reduced emissions during the transition from conventional steelmaking methods [1].

As stated above, conventional steel production is one of Europe's biggest sources of CO_2 emissions. The continent's steel industry currently contributes approximately 4% of total European CO_2 emissions, and 22% of industrial CO_2 emissions. Energy- and carbon-hungry upstream operations, such as the production of coke and iron, account for approximately 90% of these. Most emissions come from the 30 or so integrated steel plants that produce almost two-thirds of Europe's steel [1].

The majority of European steel (60%) is made via the primary route. It involves processing iron ore

to produce iron sinter or pellets, and then melting these in a blast furnace with coke to make pig iron. This is processed in a basic oxygen furnace to create steel [1]. The rest of Europe's steel comes from the secondary route. It produces steel from scrap metal by heating it in an electric arc furnace (see Figure 1 above).

Primary route processes emit mainly direct greenhouse gases. The secondary route emits mainly indirect greenhouse gases, which vary depending on the electricity mix used in the EAF. As the biggest offender, the primary route is the industry's main target to lower emissions. With global production of crude steel set to rise by 30-50% by 2050 according to an OECD long-term study, it has already taken action [1].

Methods such as coke dry quenching and optimizing pellet ratios, as well as BF equipment like top gas recovery turbines, reduce conventional primary route carbon emissions. Replacing coke with natural gas can also significantly cut CO_2 in primary steelmaking, as can injecting hydrogen or ammonia into the BF to partly replace pulverized coal. However, many of these initiatives are already standard across the industry. And none can ever achieve carbon neutrality because they don't completely remove carbon from the steelmaking process [1].

Lower secondary route emissions can be achieved by making savings on the electricity used to power the EAF, or shifting the electricity mix towards renewables. This, in theory, makes carbon neutrality possible. The problem is, the secondary process is limited by the availability of scrap, and cannot produce all steel grades or required quantities [1].

Table 8 – Greenhouse gases emissions by the primary and secondary routes of steelmaking. Source: [1].

Primary route processes emit mainly direct greenhouse gases	The secondary route emits mainly indirect greenhouse gases, which vary depending on the electricity mix used in the EAF
Industry's main target to lower emissions to reduce conventional primary route carbon emissions: + Coke dry quenching + Optimizing of pellet ratios + BF equipment like top gas recovery turbines + Replacing coke with natural gas can also signifi-cantly cut CO_2 in primary steelmaking + Injecting hydrogen or ammonia into the BF to partly replace pulverized coal	Lower secondary route emissions can be achieved by: + Making savings on the electricity used to power the EAF + Shifting the electricity mix towards renewables making carbon neutrality possible
Limitations:	Limitations:

-Many of these initiatives are already standard across the industry -None can ever achieve carbon neutrality because they don't completely remove carbon from the steelmaking process	- The secondary process is limited by the availability of scrap, and cannot produce all steel grades or required quantities

- There is therefore a clear need for a new breed of primary route technologies that can produce carbon-neutral steel
- Many of these are already in development, with some in the pilot phase and others technologically ready to go

A case study for China gives an excellent picture of the overall carbon flow in the iron and steel process (Figure 17). According to such case study, producing one ton of crude steel emits 1418.78 kg of carbon dioxide. The study decomposed this direct CO_2 emission by process—422.75 kg from fuel gas dissipation, 28.00 kg in slag, 62.94 kg in chemical products, for example. This decomposed carbon flow identified that enhancing power generation efficiency using the combined cycle could eliminate 134.43 kg CO_2 [4].



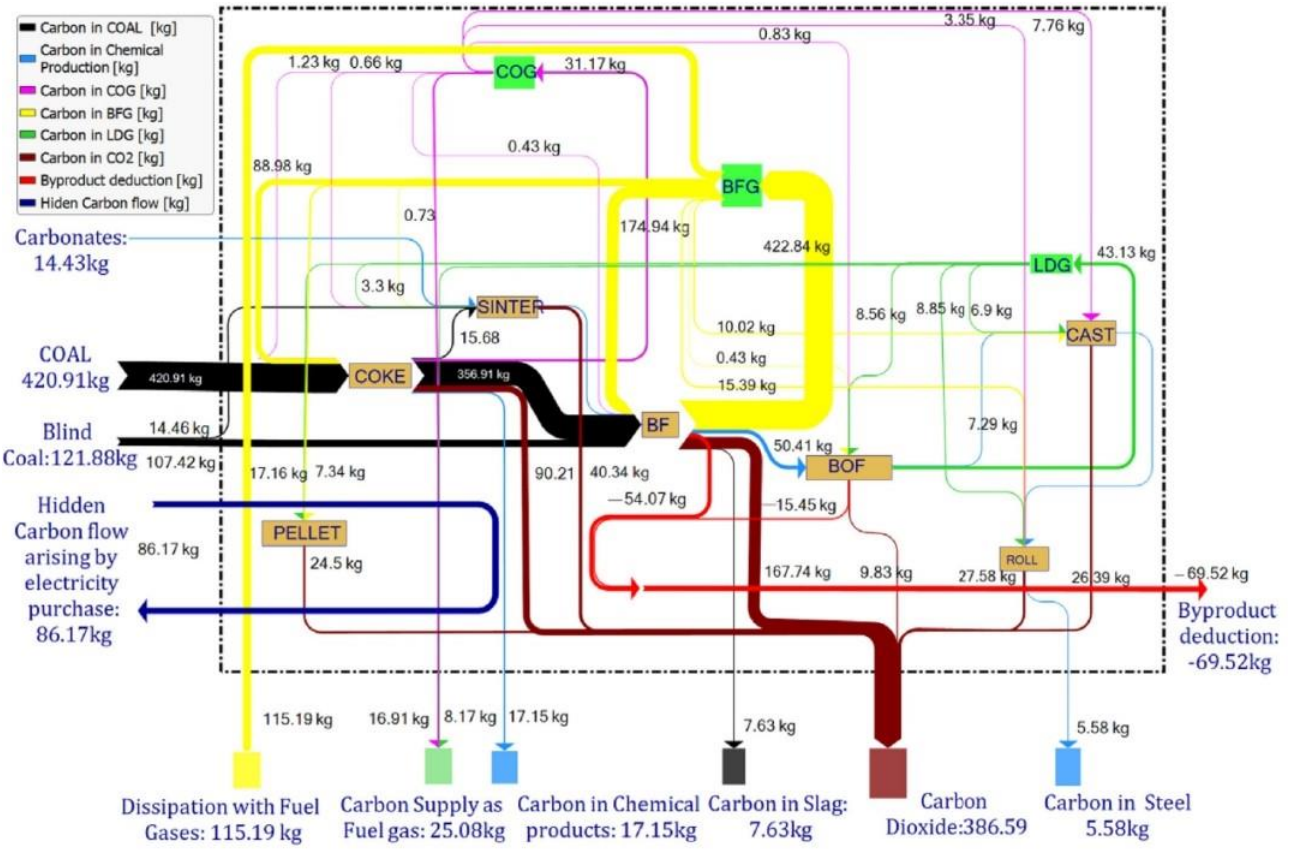


Figure 17 – A carbon flow chart for BF/BOF steel processing. Source: [4].

Applying decarbonization options for the iron and steel industry can also reduce air pollutants, such as particulate matter [4]. One study interestingly formulated the relationship between CO_2 reductions, PM2.5 reductions, and related costs through a triangular diagram (Figure 18). It is noteworthy that the balance between cost, carbon emissions reduction and particulate emissions reductions varies by technology combinations with the BF-BOF being inexpensive but very environmentally unfriendly and the combination of EAF-CCS-fabric filter and desulfurization being expensive but very environmentally friendly [4].

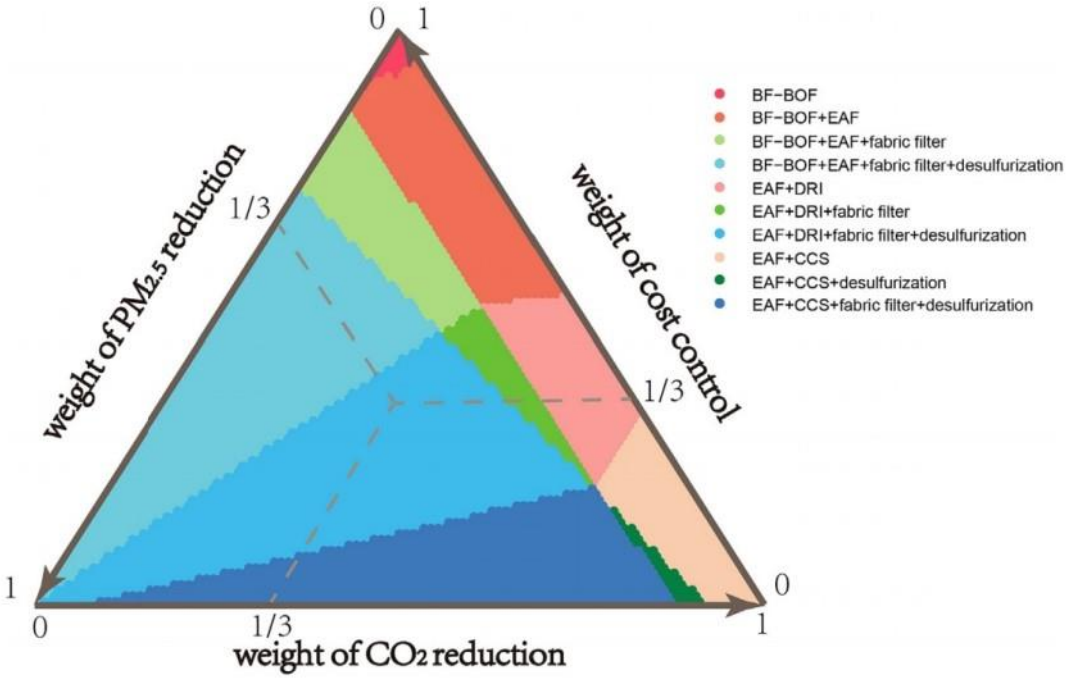


Figure 18 – Relationship between CO_2 reductions, PM2.5 reductions, and related costs of the iron and steel sector. Source: [4].

2.7 Circularity and best practices in the steel industry

The recycling ratio of steel is very high in the industry, close to 95%, making steel the most recycled material. While the high recycling ratio is mainly for economic reasons, it provides other environmental benefits that include less energy use and fewer carbon emissions. The scrap-based EAF is greener than the other steel making processes starting from raw materials. The 4-Rs “circular economy” concept shown in Figure 19 and created by the World Steel Association successfully depicts the coenvironmental benefits of reuse and recycling [4].

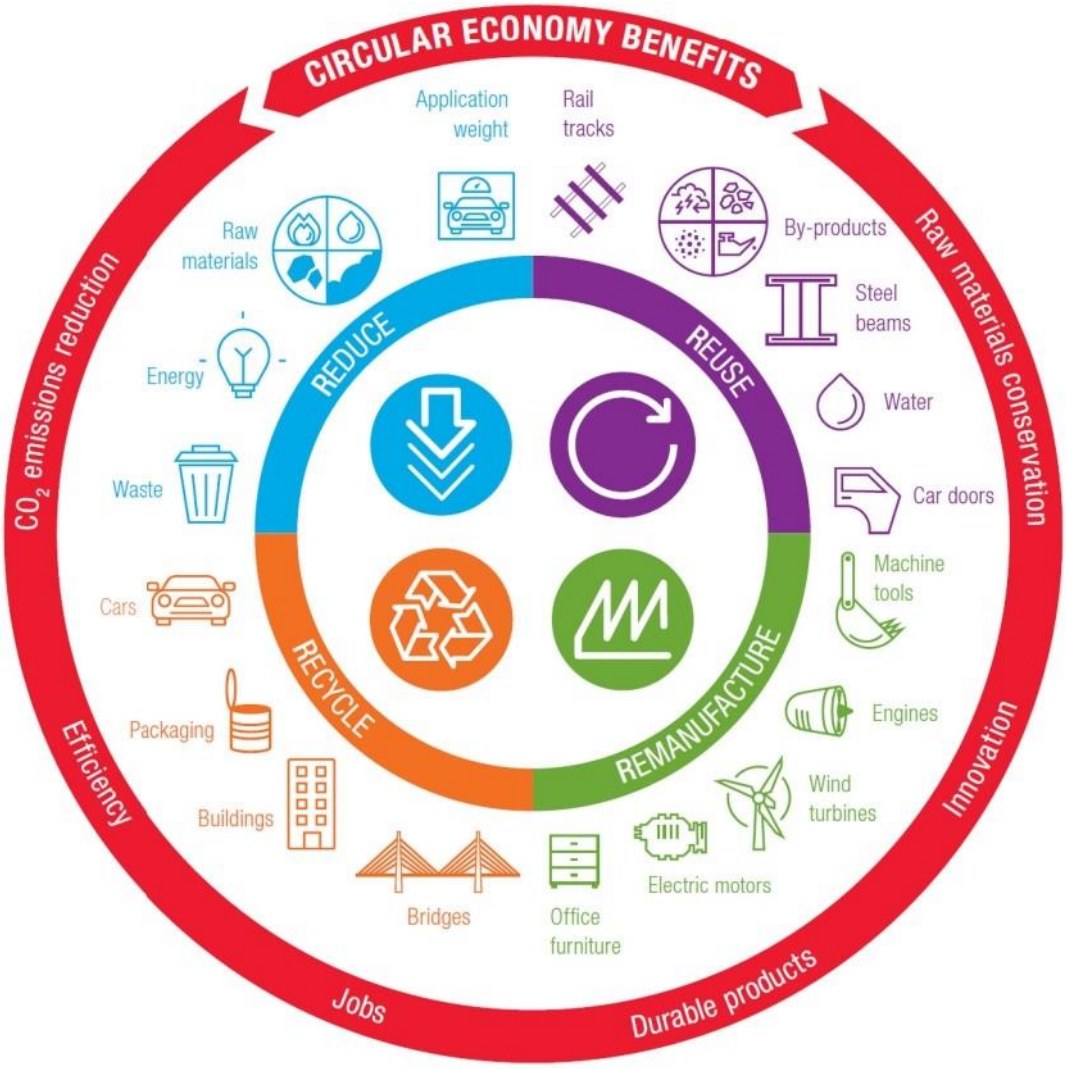


Figure 19 – Steel in the circular economy: the 4Rs. Source: [4].

2.7.1 Slag production and use

Iron- and steelmaking slags can be used as substitutes for virgin materials in several industrial applications [3]: i) Fertilisers [10]; ii) Construction [11]; and iii) Bulk material industries [12]. Blast furnace in particular forms a vital input to the cement industry, where it can be used as a substitute for clinker. Slag and other clinker substitutes are typically used to form shares of up to 40-50% by weight in the final cement product, leading to a near-halving in the emission intensity of production in the cement sector. In 2020, EUROFER has reported a total steelmaking derived slag use of 33 200 000 metric tonnes (Figure 20).

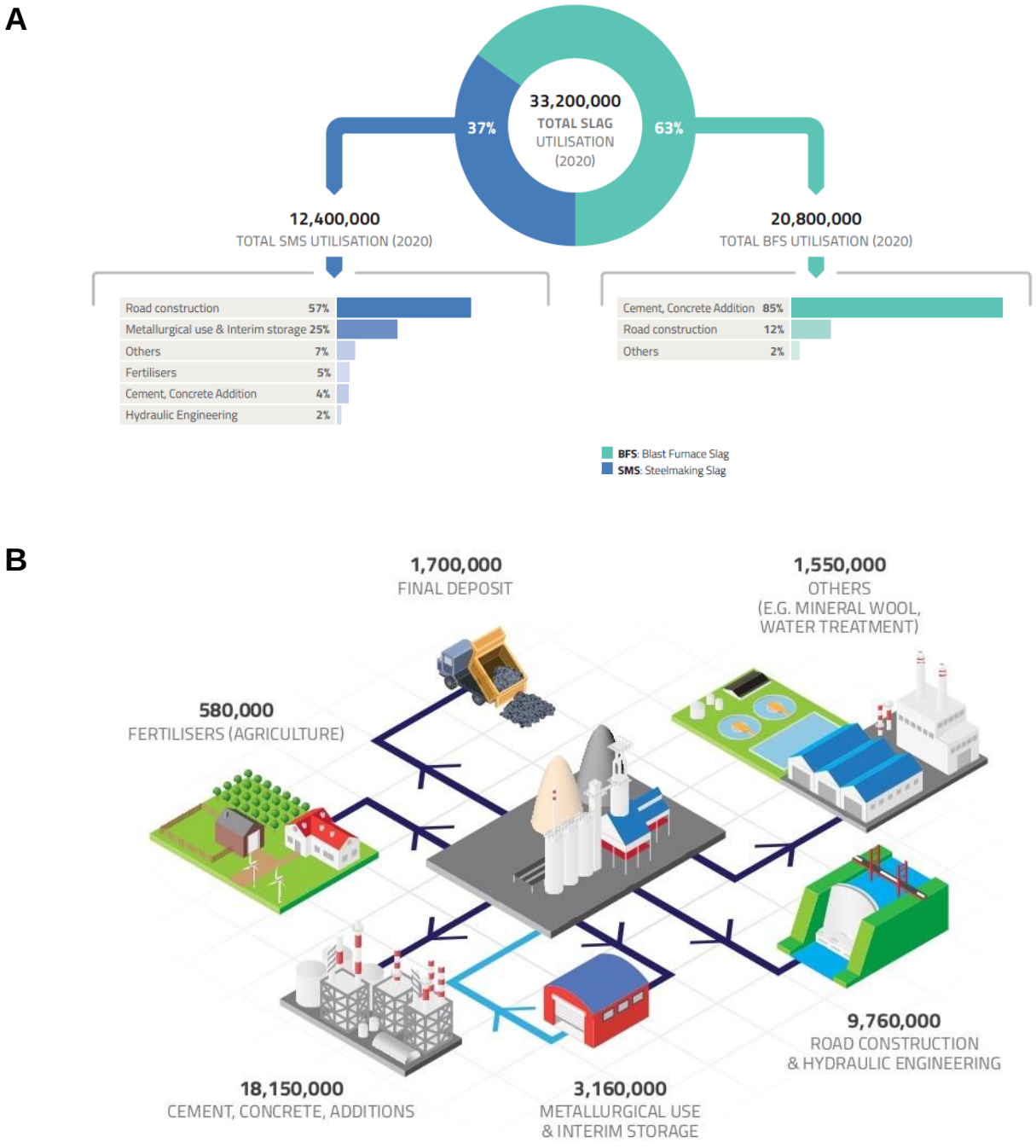


Figure 20 – A) Use of slag in downstream industries and B) Schematic use paths of slag in synergistic sectors. Source: [2].

2.7.2 Raw materials

The iron and steel sector uses carbon intensive raw materials for steel production. It is the largest consumer of coal, and DRI needs hydrogen, typically via natural gas, as a reducing agent. Thus, substantial amounts of carbon from the raw materials can be mitigated by using low-carbon hydrogen solid recovered fuels, or bioenergy sources, as the reducing agent [4].

Manufacturers can use solid recovered fuels (SRF) in steel production instead of reducing agents such as coke, coal, or natural gas. Using SRF may not be effective to reduce greenhouse gas emissions, but it could reduce landfill waste disposal, which is one of the major sources of methane emissions. Also, SRF has good properties for iron and steel making as it contains high carbon and hydrogen contents, which are necessary for strengthening steel. The steel plants in Austria, Germany, and Japan have used SRF as reducing agents. Figure 21 presents the flows of recycled wastes usage in a metallurgical plant [4].

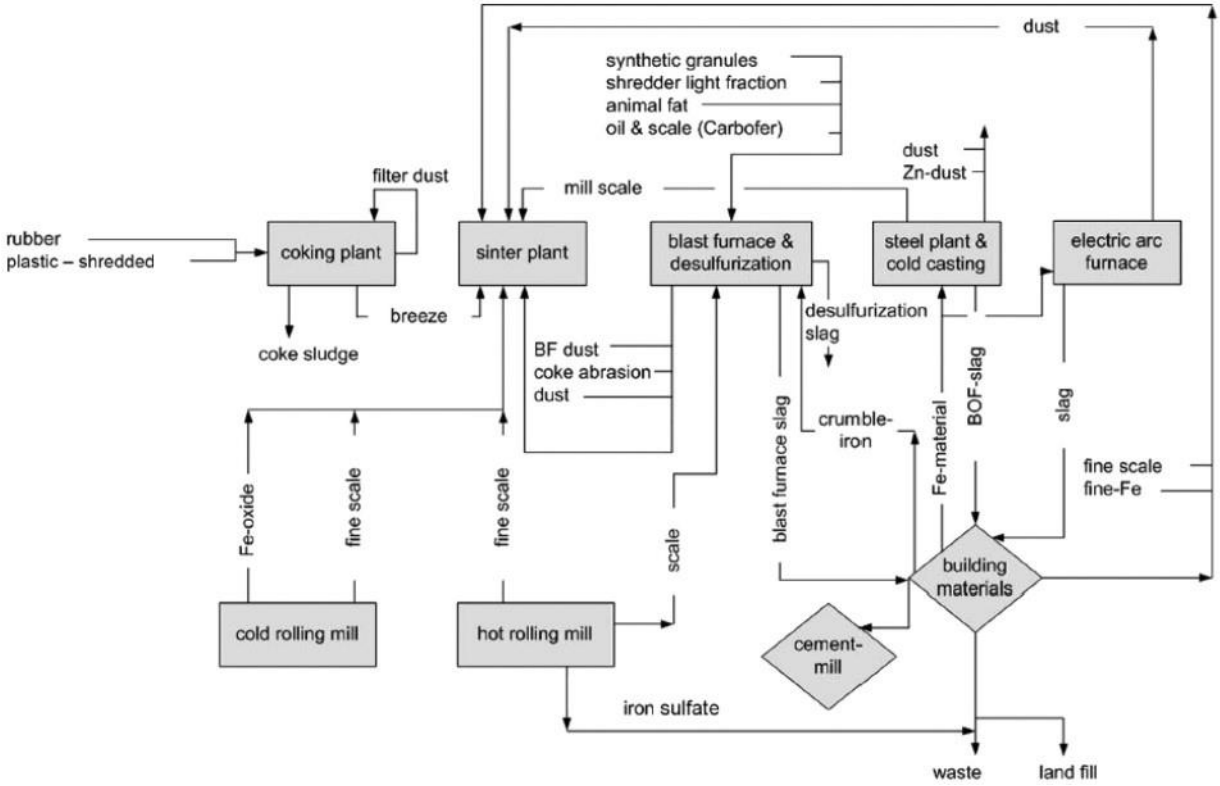


Figure 21 – Recycling of waste materials for a metallurgical plant. Source: [4].

2.7.3 Iron and steelmaking

The iron and steel making processes are the major carbon emissions source in the iron and steel industry. The iron making process is the most energy-consuming process among all steel industry processes, accounting for 70% of the total energy use of the iron and steel sector. Because of the complexity and different steelmaking routes, there are many options for decarbonizing iron and steel making processes. They include energy efficiency, adoption of renewable sources or fuel switching, waste heat recovery technologies, process integration and optimization, carbon capture and storage, and hydrogen use [4].

2.7.4 Energy efficiency

Energy efficiency is vital for the sustainable future of the iron and steel industry. Energy cost takes 20– 40% of steel manufacturing costs, and, naturally, there is a strong incentive to save energy consumption in the process. Many countries have tried to improve the energy and resource efficiency of iron and steel production. One study reveals that the Swiss metals sector, which is responsible for about 14% of the industry's total final energy demand, has the maximum energy efficiency potential at 19% with the current best available techniques. The economic potential, however, decreases in the range of 11%–15%, and the corresponding CO_2 abatement potential is 6%. Another study suggested that the whole iron and steel-making process energy utilization efficiency was 47.6%, which means 52.3% of total purchased energy was lost in the process [4].

2.7.5 Fuel switching

The adoption of renewable sources or fuel switching from fossil fuels in the iron and steel making processes can reduce substantial greenhouse gas emissions. Adopting biomass in the processes is the first option for the iron and steel industry. Biomass could replace fossil-based reducing agents and has the potential to decrease CO_2 emissions up to 50% in the integrated steelmaking process. Biochar can be used in the sintering process, and charcoal is a promising substitute in blast furnaces. Besides biomass, the other renewable sources can also mitigate carbon emissions since the industry uses electricity and heat for steel making [4].

Due to the energy intensive nature of steelmaking processes, the integration of lower-emission energy sources in high-producing geographic regions can also significantly lower global steel emissions. Coal currently accounts for 60% of China's electricity generation, which raises embodied steel emissions relative to regions that have integrated lower-emission electricity sources and renewables. Similarly, almost one-fifth of all steel is expected to come from India by 2050 (compared to around 5% today), who's electricity gird is also heavily dependent on coal. Renewable-based electricity and heat supply combining low-carbon hydrogen and CCUS could be a powerful option for decarbonization, especially as these nations continue to account for larger percentages of steel production [4].

2.7.6 Heat recovery

Waste heat recovery technologies also have great potential for the decarbonization of the iron and steel industry. Coke oven gas (COG) or coke gas is a by-product of the coke-making process in the iron and steel industry. COG is a complicated mixture of CO, CO_2, H_2, CH_4, and N_2, and volatile coal produces COG in the coking process. COG also contains around 30 wt% tar. COG, including tar,



has very high energy content that could meet approximately 4.1% of the global demand for power generation. Therefore, the hot COG utilization (recovery) can contribute considerable energy savings [4].

Various COG utilization approaches, such as power generation, H_2 production, and methanol or CH4 production, have been developed. The integrated COG-based DRI plant is another promising and efficient option. In this process, the hot DRI reacts with sulfur (in-situ desulfurization) before the fuel is injected into the reformer. Purified COG can also be converted into a reformed gas that can produce DRI [4].

Molten slag is another promising source for waste heat recovery. It is exhausted with a very high temperature around 1450–1550 ◦C. For the heat recovery from molten slag, traditional technologies, such as water quenching, is not appropriate because it consumes a considerable amount of water. POSCO, the steel company in the Republic of Korea, developed an energy-efficient technology to recover slag heat in 2012. It recorded a 50% recovery rate at a temperature of 460 ◦C in a field test of a prototype [4].

2.7.7 Process integration

Process integration and optimization is another good option to decarbonize the iron and steel industry. Various optimization techniques have been applied for the iron and steel sector, such as an integrated steel plant system, energy intensity optimization, and material energy nexus flow combination. A study illustrated the concept of mass-thermal network optimization and summarized their classifications, which gives valuable insights into the decarbonization options. As shown in Figure 22, process optimization can reduce energy demand as well as recover energy use. Thus, the optimal integration of various process optimization techniques has excellent potential as a promising decarbonization option for the iron and steel industry, and that's why a practical roadmap is necessary [4].



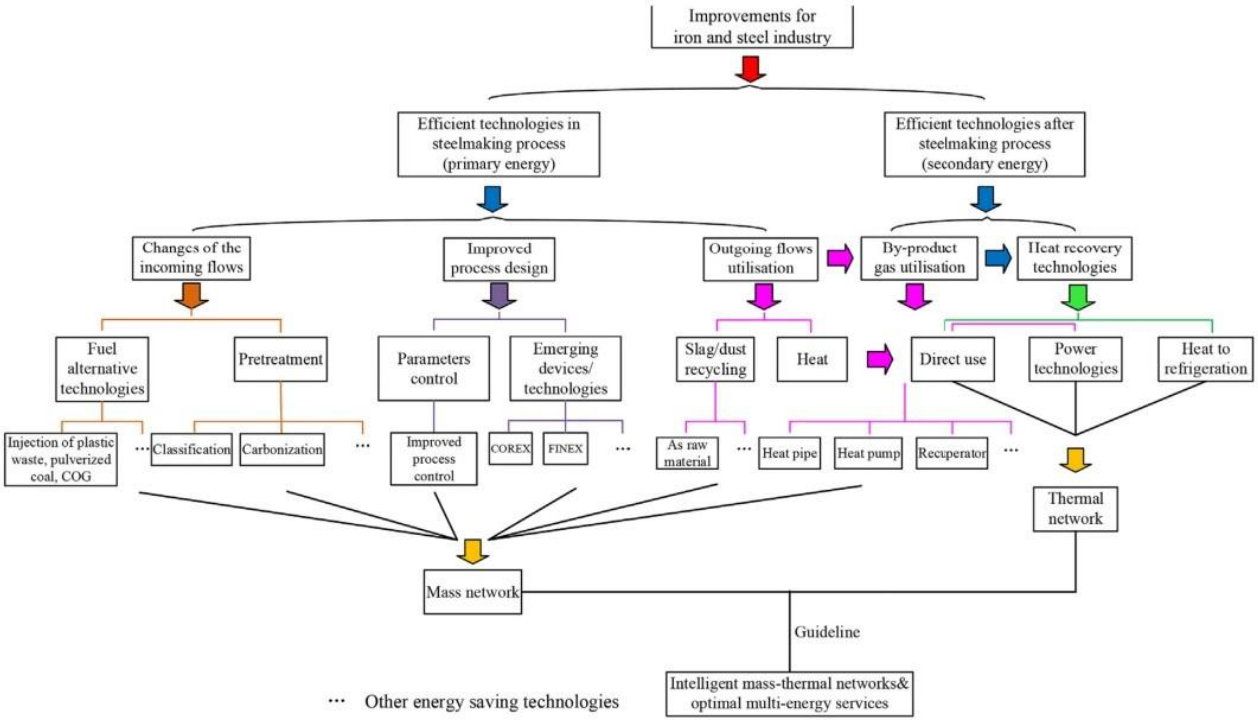


Figure 22 – Roadmap of efficient use of energy in iron and steel industry. Source: [4].

2.7.8 Carbon capture, storage and utilization

Carbon capture and storage (CCS) or Carbon capture, utilization, and storage (CCUS) technology is one of the key options to mitigate carbon emissions and hence could be helpful for the iron and steel industry. For example, there are vigorous efforts to develop effective sorbents for CCS from materials and by-products of the iron and steel making process, such as a mixture of magnetite (Fe3O4) and iron (Fe) and direct gas-solid carbonation of steel slag. Also, CCUS includes “off-gas hydrogen enrichment and/or CO_2 removal for use or storage,” “converting off-gases to fuels,” “converting off-gases to chemicals” for blast furnaces (BF), and “natural gas-based with CO_2 capture” for direct reduced iron (DRI). Because of its versatile nature, CCS can be applied for most processes in the sector: sintering, pelletizing, coking, iron and steel making, and casting and rolling [4].

An increase in CO_2 costs in the market, i.e., the EU Emission Trading Scheme, can make CO_2 capture options economically feasible in the iron and steel industry. Note that iron and steel manufacturing is an extensive production process with high CO_2 concentrations and recoverable heat. Higher carbon price thus makes the CCS applications in the iron and steel industry economically feasible. Despite the challenges to meet economic feasibility, it is evident that CCS will be (and must be) an effective and cross-cutting option for the decarbonization of the iron and steel sector [4].

As many steelmaking practices have already reached close to their maximum thermodynamic limits and emerging decarbonization options are primarily focusing on incrementally lowering emission, carbon capture is one of the few technologies to offer scalable reductions that rival steel's economic importance and need for decarbonization. Several studies discuss its technical concept, application design, and potential as a promising decarbonization option [4].

2.7.9 Waste and recycling

Reducing wastes in the steel making processes and recycling steel products can substantially reduce energy use in the iron and steel sector. The World Steel Association reveals that the steel industry has globally recycled over 22 billion tons of steel since 1900, resulting in the iron ore (28 billion tons) and coal (14 billion tons) consumption reduction globally. Another study showed that global secondary steel using steel scrap may expand to 38% of total steel production by 2050. Since steel production from scrap uses much lower energy than the primary steel from iron ore, the expansion of secondary steel can be an impactful decarbonization option [4].

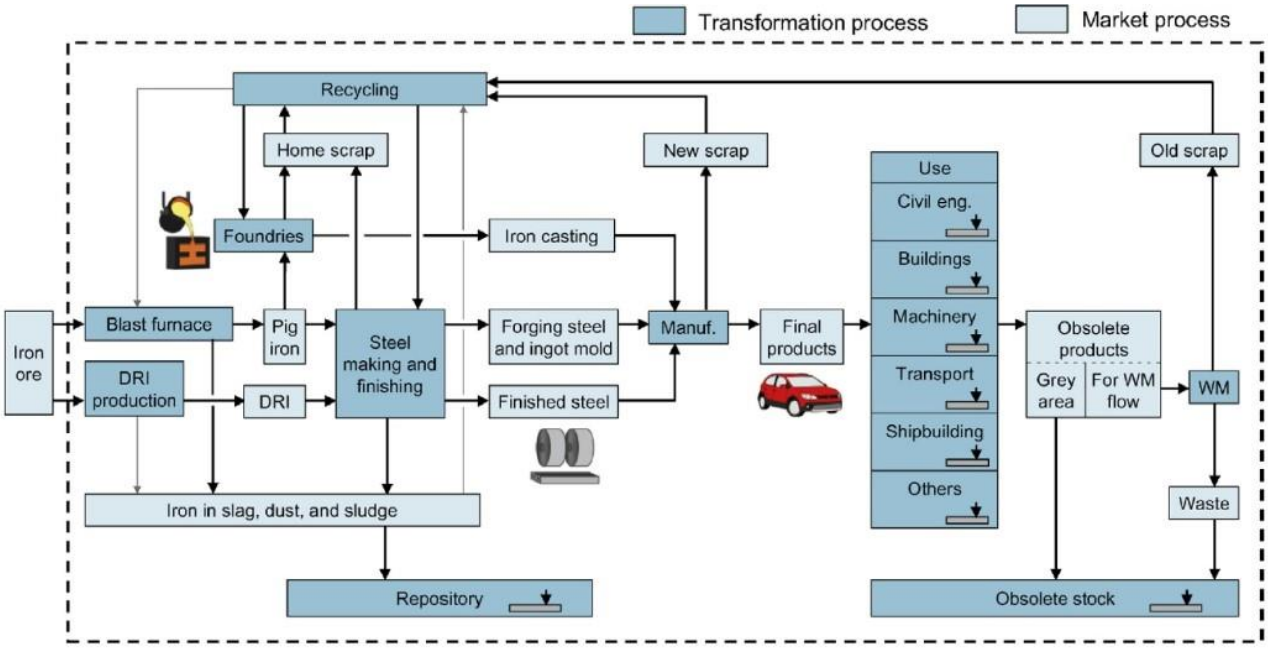


Figure 23 Steel scrap recycling. Source: [4].

Iron recovery from metallurgical slags is also noteworthy and Ewastes, such as refrigerators, computers, and TV, also provide secondary ferrous resources for recycling. Comminution (for size reduction and surface area increase) and separation, carbothermic smelting reduction, carbothermic reduction, flotation, or leaching, and aluminothermic smelting reduction technologies have been applied for the iron recovery from slags [4].

Recycling steel for use as a raw input, or for the creation of recycled steel through EAF production routes can also lower the emissions intensity of steel by 62–90%. The amount of emissions reduced is primarily based on the electricity grid of the country that is responsible for recycling the steel, the steel process route, and is heavily dependent on the availability of scrap steel. Because of this dependency, and steel's use in products with long lifetimes, the use of recycled steel has not been able to match growing steel demand, although many of the IEA's ambitious climate scenarios show large increases in the creation of scrap-base steel and a decline in blast-furnace primary steel production [4].

2.9 Options for decarbonisation

To achieve the drastic reductions needed, an entirely new, transformative approach to ironmaking is required, and there are several promising approaches to ironmaking at an industrial scale without the release of CO_2 [13]. The transition to a low-carbon world requires a transformation in the way iron and steel are manufactured. There is no single solution to CO_2-free steelmaking, and a broad portfolio of technological options is required, to be deployed alone, or in combination as local circumstances permit. This section describes and explores the status of a number of key technologies and issues based on analysis published by the Worldsteel Association [13]. These fall into following four broad categories: biomass, carbon, hydrogen and electricity. Additionally, several projects that fall in those categories are currently being developed worldwide (Table 9).

Table 9 - *Several projects are under development worldwide*. Source: [5].

Category	Project name and description / leading company
Carbon	**Northern Lights** [14] ArcelorMittal commits to cooperation on Equinor-led carbon capture and storage project to reduce CO² emissions. ArcelorMittal, the world's leading steel and mining company, has signed a memorandum of understanding with international energy firm Equinor to develop value chains in carbon capture and storage. Equinor is a partner in the Northern Lights project, together with partners Shell and Total, which includes transport, reception and permanent storage of CO_2 in a reservoir in the northern part of the North Sea. As part of the project, ArcelorMittal – which has an ambition to be carbon neutral by 2050 within Europe has committed to a number of joint activities including the development of logistics, exploring potential commercial models, and advocating on the topic of carbon capture and use (CCU) and CCS, as an important part of the successful decarbonisation of

European industry. The company's primary role will be the capture of CO_2 gas from its blast furnaces.

At the end of 2019, the partnership plans to drill a wildcat well for CO_2 storage in the Johanson formation covered by the Aurora licence (EL001) to study the reservoir's suitability and capacity for CO_2 storage.

BAO-CCU [15]

BHP has signed a memorandum of understanding (MOU) with world leading steel producer, China Baowu, with the intention to invest up to US$35 million and share technical knowledge to help address the challenge of reducing greenhouse gas emissions facing the global steel industry.

The five-year partnership will focus on the development of low carbon technologies and pathways capable of emission intensity reduction in integrated steelmaking. Under the MOU, the deployment of carbon capture, utilisation and storage in the steel sector will also be investigated at one of China Baowu's production bases.

BHP Chief Executive Officer, Mike Henry, said the companies would collaborate on technical solutions to utilise low carbon fuel sources such as hydrogen injection in the blast furnace, and explore other low emission options in support of China Baowu and the steel industry's low carbon transformation and green development goals.

Last month BHP awarded a tender for world's first LNG-fuelled Newcastlemax bulk carrier to carry iron ore between Western Australia and China, which will reduce emissions by more than 30% per voyage.

The Carbon2Chem® project [16]

Carbon2Chem® aims at using emissions from steel production as raw material for chemicals. "We will use surplus energy from renewable sources in the process. Thus, the project is an essential contribution to climate protection as well as energy transition."

"As a diversified industrial company we are both steel producers and builders of chemical plants. This is why we play a leading role in developing the technology. It will take about 15 years until the concept will be applicable on an industrial scale."

Al Reyadah Carbon Capture, Use, and Storage (CCUS) Project [17]

This is an integrated commercial-scale project, located in Mussafah, Abu Dhabi, United Arab Emirates, which is capturing carbon dioxide (CO_2) from the flue gas of an Emirates Steel production facility and injecting the CO_2 for enhanced oil recovery (EOR) in the Abu Dhabi National Oil Company's nearby oil fields. The main objectives of the project are to reduce

	the carbon footprint of the United Arab Emirates, implement EOR in subsurface oil reservoirs, and free up natural gas that would have been used for oil field pressure maintenance. The Al Reyadah Project includes capture, transport, and injection of up to 800,000 tonnes per year of CO_2 (processed at the required specifications and pressure) and is part of an overall master plan which could also create a CO_2 network and hub for managing future CO_2 supply and injection requirements in the United Arab Emirates.
	HISARNA [18] • Shows the commitment of the European steel industry to structurally reduce CO_2 emissions • Reduces CO_2 emissions by at least 20% • Reduces energy consumption by at least 20% • Reduces emissions of nitrogen, sulphur oxides and nitrogen oxides • Leads to a more efficient use of raw materials and residual materials ideal for capturing and storing or using CO_2 • Lowers the operating costs of steelmaking
	Steelanol [19][20] The technology that will be developed and proven in this project will allow for the capture and reuse of a portion of carbon emitted by the steel industry without need to rebuild the BAT (Best Available Technologies) steel plant while supplying the transport sector with high grade biofuel, that does not compete in any way with food crops or land for food crops. It should also be noted that while other renewable sources such as water and wind can be used to create electricity, fuels require carbon and thus cannot be created without a carbon-rich source. This technology therefore provides the unique opportunity to recycle the carbon from industrial exhaust rich gases that would otherwise be emitted into the atmosphere. By proving the compatibility of this technology with the high quality requirements of fuel grade fuels, the partners will demonstrate the application potential of this process – that could potentially lead to the displacement of a high amount of fossil fuels in the transport sector and beyond.
Hydrogen	**COURSE 50** [21] It aims at developing technologies to reduce CO_2 emissions by approximately 30% through suppression of CO_2 emissions from blast furnaces as well as capture - separation and recovery - of CO_2 from blast furnace gas (BFG), and establishing the technologies by ca. 2030 with the final goal of industrializing and transferring the developed technologies by 2050
	HBIS & Tenova [22] This will be the world's first DRI production plant powered by hydrogen enriched gas, which

	will make use of the most advanced, competitive, eco-friendly and reliable, which includes advanced digital models for equipment and metallurgical behaviour prediction
	HYBRIT [23] • Pursuing the transition towards a fossil-free value chain from mine to steel using fossil-free electricity and hydrogen • Providing the technical conditions for minimizing carbon dioxide emissions from the iron and steel industry • Creating a research and development platform for companies in the value chain to collaborate and create the best conditions for fossil-free steel
	Novel Flash Ironmaking Process [24] The project goal is to develop an entirely new transformational process for alternate ironmaking based on the direct gaseous reduction of iron oxide concentrates in a flash reduction process, with the ultimate objective of significantly increasing energy productivity (by reducing energy consumption by up to 57 %) and reducing environmental emissions, especially CO_2 emissions, versus the conventional blast furnace ironmaking route. The Novel Flash Ironmaking Process uses gaseous reducing agents, such as natural gas, hydrogen, other syngas, or a combination thereof. The proposed technology is to be applied to the production of iron as a feed to the steelmaking process, eventually replacing the blast furnace and other alternate ironmaking processes. The process can also be a part of a continuous direct steelmaking process.
	SuSteel [25] SuSteel (sustainable steel) represents a research and development project for a CO_2 free production of crude steel. The technology is based on the usage of hydrogen plasma. Thereby, hydrogen is used as the reduction agent for the iron ore while its plasma state offers the thermal energy for melting the metallurgical iron. The utilisation of hydrogen as the reduction agent inheres the advantage that only gaseous water remains as by-product. Consequently the usual emissions of CO_2 can be fully avoided. The main foci of this research are the generation and perpetuation of the hydrogen plasma, the impact of hydrogen on the refractory lining, and the very details about the process and operational parameters.
Electricity	**Boston Metals** [26] Boston Metal has developed a game-changing electrolysis process for making steel. Electrolysis is an electro-chemical process that uses direct electric current to separate chemical compounds into their constituent parts.

	Our Molten Oxide Electrolysis (MOE) technology is simpler, smarter, and greener than conventional steelmaking. In our MOE cell, an inert metallic anode is immersed in an electrolyte containing iron ore and then electrified. The cell heats to 1600ºC and electrons split the bonds in the iron ore. The result is a clean, high purity liquid metal that can be sent directly to ladle metallurgy — no reheating required.
	Siderwin [27] It proposes a breakthrough innovation, compared to the actual steel production process, bringing together steel making with electrochemical process. An electrolytic process, flexible enough to be supplied by renewable energies, will transform iron oxides, including those inside the byproducts from other metallurgies, into steel plate with a significant reduction of energy use. This process decomposes under mild conditions but at intense reaction rates naturally occurring iron oxides such as hematite into iron metal and oxygen gas. By offering a CO_2-free steel production process, the project will contribute to the reduction of the total greenhouse gas emissions. Compared to traditional steelmaking plants, this innovative technology has several positive impacts such as: • a reduction by 87% of the direct CO_2 emissions, • a reduction by 31% of the direct energy use, • the ability to produce steel from by-products rich in iron oxides from non-ferrous metallurgy residues, and • an increased integration with renewable energies with a more flexible process.
Hydrogen / Electricity	**Salcos** [28] **via the GrInHy2.0 project** [29] Essential element of the GrInHy2.0 project is to produce hydrogen the most energy efficient way while increasing the technological maturity of the High-Temperature Electrolyser (HTE). Although starting with hydrogen production for today's steel annealing processes, GrInHy2.0 marks an important milestone towards a hydrogen-based, low carbon European steel industry. Here, hydrogen has the potential to reduce today's process related CO_2 emissions by more than 95 %. GrInHy2.0 will contribute to a detailed analysis of the potentials of renewable hydrogen in the iron-and-steel industry as well as the in-depth understanding of SOEC long-term behaviour on stack level.

With the first implementation of a high-temperature electrolyser of the Megawatt-class, GrInHy2.0's prototype will produce 200 Nm³/h of hydrogen at nominal power input of 720 kWAC. The HTE system consists of up to eight modules with 720 or 1,080 SOECs each, i.e. 24 or 36 stacks, respectively.

As in the predecessor project GrInHy, the prototype will be fully integrated into Salzgitter's steelmaking operations and will run on steam from waste heat of the steel production. By the end of 2022 it is expected to have been in operation for at least 13,000 hours, producing a total of around 100 tons of high-purity 'green' hydrogen at electrical efficiency of minimum 84 %LHV.

In parallel to the prototype testing operation, a singular stack of the SOEC technology will set new standards in long-term testing with a test bench operation of at least 20,000 hours. The test will not only show the technology's increased robustness but also provide potential starting points for further improvement.

In a broader perspective, the project will also deliver answers on how to avoid CO_2 emissions in the European steel industry by switching to a hydrogen-based primary hydrogen is therefore steelmaking and what it takes.

H2FUTURE [30]

The project builds on combining state-of-the-art PEM electrolyser technology with grid services and integrating both into the steel manufacturing process.

voestalpine's and K1-MET's approach of stepwise decarbonisation of steel production by primarily focused on natural gas as bridge technology in the direct reduction process in addition to the conventional route and – in the long term –on the transfer to process routes like direct reduction based on the use of "green" hydrogen and electric arc furnace.

Large scale hydrogen production in the H2FUTURE project is an important pillar in order to turn this vision into reality. Testing PEM (proton exchange membrane) electrolysis technology on an industrial scale (6 MW) and simulating rapid load changes in electricity generated from renewable energy sources and from electric arc furnace steelmaking (grid balancing) are the key elements of this European flagship project.

H2FUTURE symbolises the major challenge in developing breakthrough-technologies: broad-based and intense cooperation across company borders, e.g. between steel and energy sectors, scientific and industrial partners, and on national as well as European levels.



By Technology type, the projects presented in Table 9 can be presented in the scheme of Figure 24.

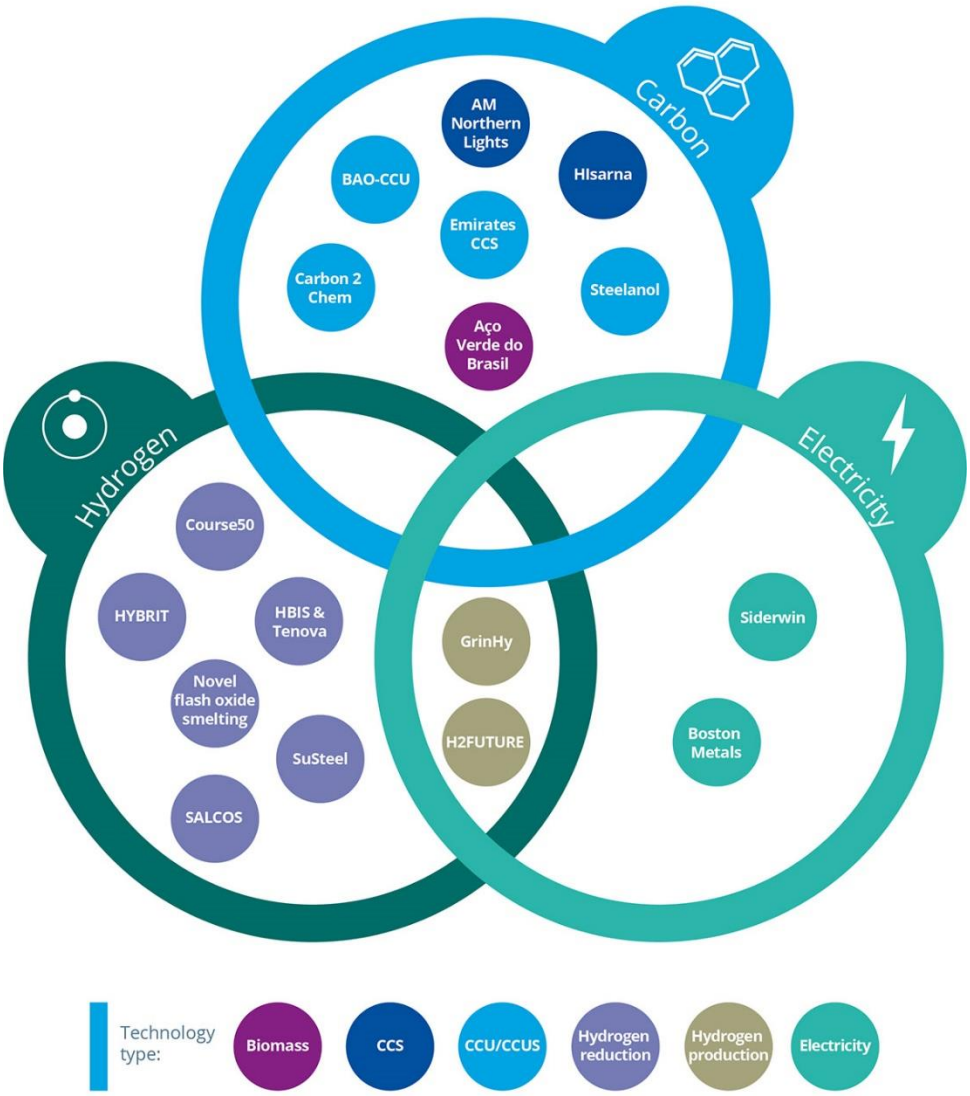


Figure 24 – Innovations in the steel industry by technology type. Source: [13].

2.9.1 Biomass in steelmaking

While some blast furnaces do currently operate entirely using biomass, the relative strength of charcoal compared to coke means that these are smaller furnaces. Charcoal is currently used commercially to substitute for a proportion of the coal used in blast furnaces, primarily in Brazil [31].

Biochar can potentially be substituted for pulverised coal currently injected directly into blast furnaces. Work was undertaken to this end under the Australian CO_2 breakthrough programme, which

focussed on substituting coal used in pulverised coal injection (PCI) in the blast furnace with sustainable biochar. Some development continues to further optimise charcoal production to improve its product specifications for steel production [31].

The Torero partnership project is testing the use of biocoal (torrefied waste wood) to partially substitute coal in ArcelorMittal's plant in Ghent, Belgium. Construction of the project started in 2018; reactor #1 is expected to start production in 2022 and reactor #2 in 2024. The two reactors will each produce 40,000 tonnes of bio-coal annually [31].

Robust supply chains exist to move the large amounts of raw materials (such as coal, iron ore, lime, scrap) required in modern steelmaking. Similar supply chains will need to be developed to harvest biomass at volume, convert and process it to char, and to deliver it reliably to steel manufacturing facilities. Transportation and processing will also generate greenhouse gas emissions. Taking an LCA approach to the assessment of emissions for the use of biomass is important in order to obtain a balanced view of the impact of biomass use on steel production [31]. The World Bioenergy Association has prepared a fact sheet focussed on supply chain issues [32].

Table 10 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based in the use of biomass.

Table 10 – Biomass-based iron making + CCUS. Source: [1].

Pros	Cons
+ **Biomass alone can cut up to 40-60% of CO_2 emissions, and in combination with CCUS can achieve carbon-neutral steelmaking** + **In the shorter term, biomass is an instant partial replacement for fossil fuels, allowing quick-win emission reductions at existing plants** + **CO_2 from emissions can also be recycled using CCUS to produce fresh biomass**	- Cultivation of biomass is problematic - Environmentally, it can lead to deforestation, pollution and reduced biodiversity, and socially, increased food prices and agricultural land use - Political and social acceptance therefore has a high risk - In addition, biomass has a lower calorific value than fossil fuels, limiting its use in large blast furnaces or lowering efficiencies - Due to its high water content, it can also be too heavy for use in large blast furnace
Example of pilot project: a biomass study by the Swedish research group SWEREA at an SSAB steel plant in Luleå identified potential for a 28% reduction in CO_2 emissions	



2.9.2 Using carbon as a reductant

Carbon capture and storage (CCS) could potentially be applied to all major point sources in the steel sector. Processes include post/pre-combustion capture, and compression-transport-store/use (Figure 25).

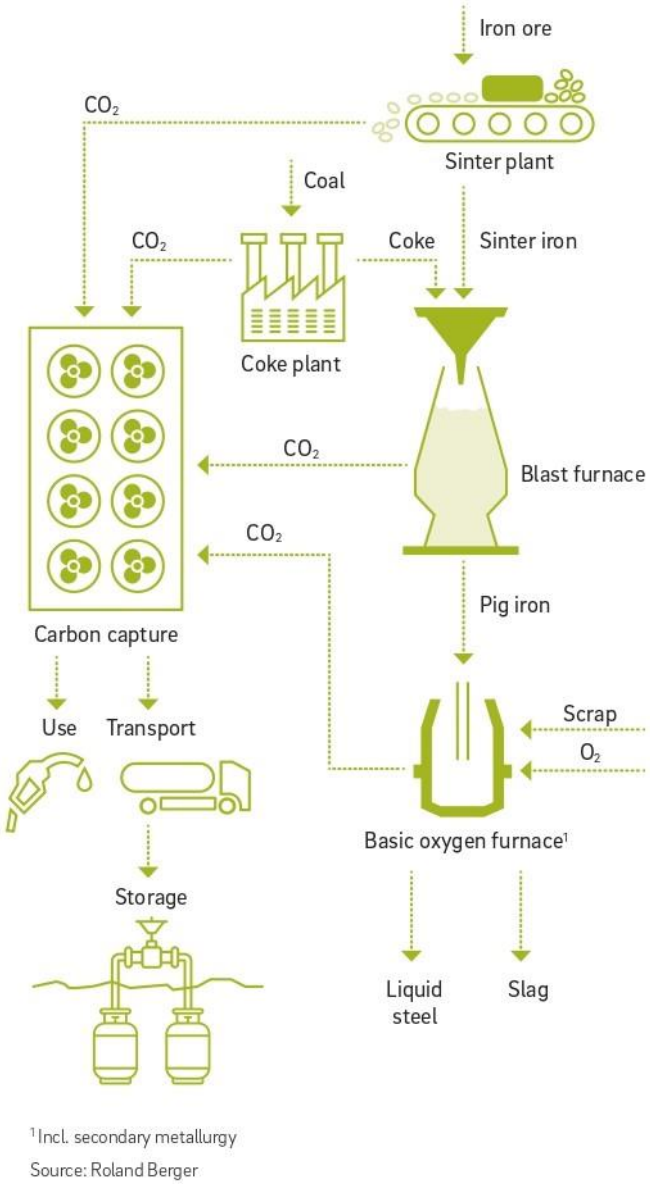


Figure 25 – Proposed carbon capture, use and storage applied to the steel industry. Source: [1].

Past studies have tended to focus on the blast furnace as the major point source of CO_2 on a conventional integrated steel plant, either using retrofitted CO_2 capture technology or by developing a new type of blast furnace. The European ULCOS programme represents a good example of the

latter – proposing a radical new top gas recycling blast furnace design. CCS has not yet been applied to blast furnace steelmaking [33].

Direct reduction plants can offer an easier route to CCS, as some plants incorporate CO_2 separation into their designs and emit a concentrated stream of CO_2 during normal operation. In these plants additional carbon capture equipment is not required. Carbon capture can potentially be retrofitted to conventional DRI facilities [33].

Innovative coal-based smelt reduction plants such as the HISARNA process piloted at Tata Steel in the Netherlands are capable of producing a concentrated steam of CO_2, negating the need for CO_2 capture technology [33].

- The DRI unit at Emirates Steel in Abu Dhabi is currently the only operational CCS plant in the iron and steel sector. This plant is capable of capturing 800kt of CO_2 per year, which is compressed, dehydrated and then pumped through 50 km of pipeline to be injected into a mature onshore oil field for enhanced oil recovery (EOR) operations. The design of the DRI unit meant that a 90% CO_2 waste stream was emitted during normal operations, so an additional capture step was not required.
- A similar plant in Venezuela emits a waste stream close to 100% CO_2, but the captured CO_2 is currently vented to atmosphere.
- CO_2 is captured for use (see CCUS factsheet) from Ternium DRI facilities in Mexico.
- Carbon capture on the blast furnace have been studied in a number of research projects – these include the Japanese ‘COURSE 50’ project, the EU ULCOS programme and current projects in Germany (ROGESA, Saarstahl) and Sweden (STEPWISE).
- A Front End Engineering Design study is currently being undertaken by ArcelorMittal looking to design a carbon capture system capable of capturing 50-70% of CO_2 emissions from blast furnace gas.
- Tata Steel is involved in the Athos project, with the aim of developing a CO_2 transport and storage network in the Dutch North Sea Canal area to enable the utilisation and storage of large volumes of CO_2.
- ArcelorMittal is working with the Northern Lights consortium. This project could potentially see CO_2 derived from steelmaking in Belgium and France shipped to Norway for geological storage.

Table 11 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on carbon capture, use and storage technologies.

Table 11 – Carbon capture, use and storage in steelmaking. Source: [1].



Pros	Cons
+ **The main advantage is that CCUS systems can be fairly easily integrated into existing conventional brownfield plants** + **As the technology is not specific to steelmaking, other industries can share development and infrastructure costs (for example, around the synthetic fuel market, transportation and storage)** + **Future operating costs are largely predictable fuel market, transportation and storage).**	- CCUS is not fully carbon neutral, as the carbon capture process alone captures only about 90% of CO_2 - Public acceptance of carbon storage is not guaranteed, disadvantaging first movers - Excepting minor onshore storage locations, the North Sea offers the only suitable large storage location in Europe, necessitating considerable transportation efforts - Utilization of emissions must rule out carbon release at a later stage for the process to be carbon neutral
Example of pilot project: *+The Carbon2Chem project, backed by industrial conglomerate thyssenkrupp, is piloting the processing of emissions such as CO_2 to make synthetic fuel* *- Currently not carbon neutral as CO_2 is emitted at a later stage*	

2.9.3 Using electrical energy through an electrolysis-based process

Electrolysis is a technique that uses direct electric current to separate some chemical compounds into their constituent parts [34]. Electricity is applied to an anode and a cathode, which are immersed in the chemical to be electrolysed. Electrolysis of water (H_2O) produces hydrogen and oxygen, whereas electrolysis of aluminium oxide (Al2O3) produces metallic aluminium and oxygen [35].

There are two potential ways to separate metallic iron from the oxygen to which it is bonded in iron ore. These are through the use of chemical reductants such as hydrogen or carbon, or through the use of electro-chemical processes that use electrical energy to reduce iron ore [35].

In electrolysis, iron ore is dissolved in a solvent of silicon dioxide and calcium oxide at 1600°C, and an electric current passed through it. Negatively-charged oxygen ions migrate to the positively charged anode, and the oxygen bubbles off. Positively-charged iron ions migrate to the negatively charged cathode where they are reduced to elemental iron. If the electricity used is carbon-free, then



iron is produced without emissions of CO_2. Electrolysis of iron ore has been demonstrated at the laboratory scale, producing metallic iron and oxygen as a co-product [35].

The EU ULCOS project examined the prospects for electrolysis based ironmaking through their ULCOTWIN initiative [36].

- The Siderwin project, being led by ArcelorMittal, is looking at using low temperature electrolysis using a water-based electrolyte. The project has been taken to TRL4, and ArcelorMittal, surrounded by 11 additional innovative European partners, aims to develop a 3 metre-long new experimental pilot to validate the technology at TRL 6. The ULCWIN pilot plant used to validate the feasibility of the technology at TRL 4 has produced 4kg iron samples.
- Research at MIT led to founding Boston Metal, which commissioned its first prototype high temperature (1,500°C) molten salt-based cell in 2014 and has produced a total of more than 1 tonne of metal. The company is now aiming to construct a pilot scale plant.

There are two types: electrolysis and electrowinning (Figure 26). Electrolysis transforms iron ore at approx. 1550°C into liquid steel using electricity as a reductant. In electrowinning, iron ore is ground into an ultrafine concentrate, leached and then reduced in an electrolyzer at around 110°C. The resultant iron plates are fed into an EAF, which turns it into steel. ULCOLYSIS is the main electrolysis method, ULCOWIN the main electrowinning one [1].



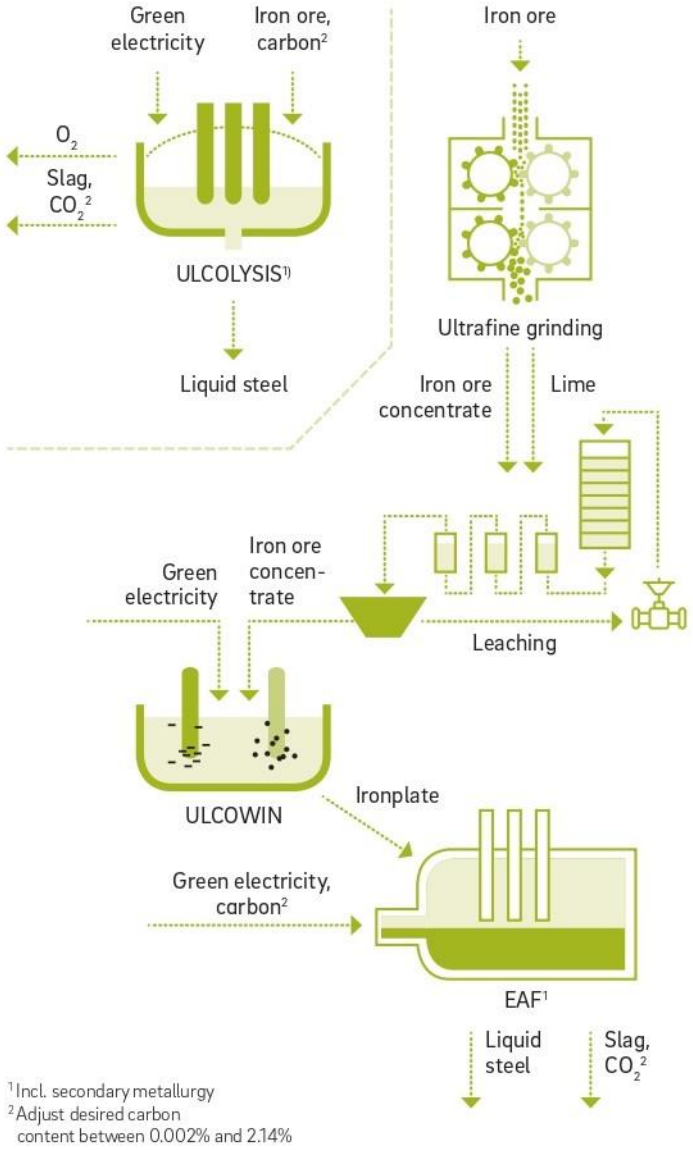


Figure 26 – Proposed electrolytic processes. Source: [1].

Table 12 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on the use of H_2 in the direct reduction of iron in a shaft furnace.

Table 12 – Electrolytic processes in the steel sector. Source: [1].

Pros	Cons
+ **Because they skip the upstream stages required in other production routes, such as producing coke or H_2 as reductants, electrolytic processes have the po-**	- The technology, especially electrolysis of iron ore, is still being tested in laboratories, suggesting a long and costly development phase - The process is also relatively inflexible compared to H_2 direct reduced iron

	tential to become the most energy-efficient steelmaking methods, especially electrolysis		methods as it cannot be stopped easily
+	**They also promise to significantly lower CAPEX as, in the case of electrolysis, only very few aggregates are needed**	-	Lastly, while green electricity remains expensive and storage possibilities few, profitability will be low as the process needs a constant source of electricity and therefore cannot take advantage of excess cheap green energy

The EU's ULCOS project, which involved many European steelmakers including ArcelorMittal, led the development of ULCOLYSIS and ULCOWIN. It demonstrated laboratory-scale high-temperature electrolysis for direct production of liquid steel.

2.9.4 Plasma direct steel production

Iron ore, raw or in the form of fines or pellets, is reduced using hydrogen plasma in a plasma steelmaking reactor (Figure 27). At the same time, carbon is added to the reactor to produce steel. Hydrogen plasma is H_2 gas that has been heated or electrically charged to separate, or ionize, it into its constituent particles [1]. The process may use either thermal plasma (produced by directly heating H_2) or non-thermal plasma (produced by passing a direct current or microwaves through H_2).

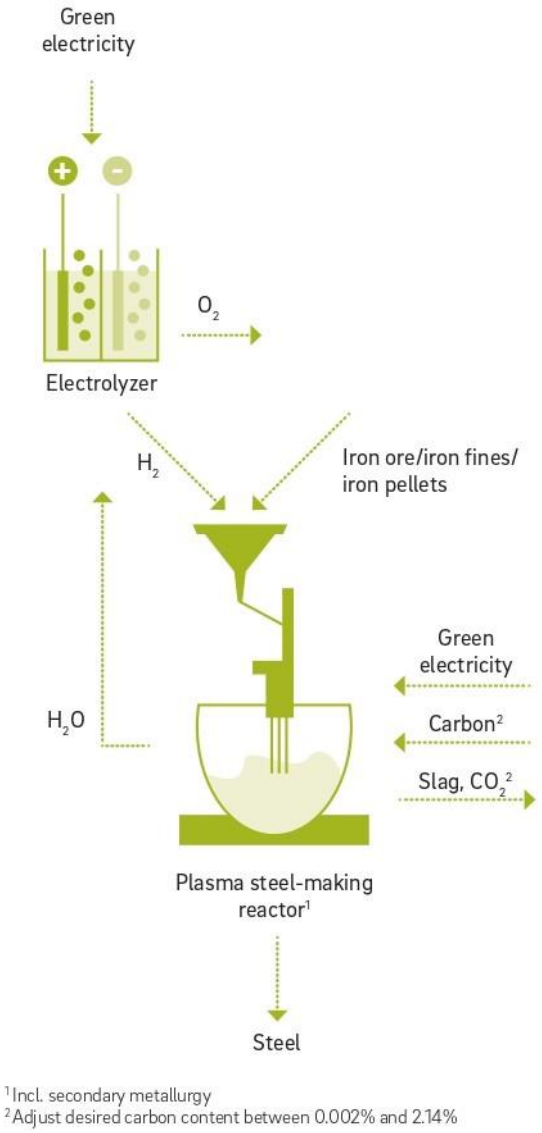


Figure 27 – Proposed plasma direct steel production. Source: [1].

Table 15 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on the use of H_2 in the direct reduction of iron in a shaft furnace.

Table 13 – H_2-based direct reduced iron – shaft furnace. Source: [1].

Pros		Cons	
+	**The process removes the need for pre-processing of iron ore and allows for lower reactor temperatures**	-	The technology is at a very early stage of development, with an optimal process and full reactor design yet to be developed
+	**It is also highly integrated, with some methods (for example, hydrogen plasma**	-	Its commercial feasibility is also still to be proven

	smelting reduction) requiring only a single step
+	**This makes it commercially attractive: if the technology was ready to use today, it would have the potential to reduce costs significantly**
+	**As well as offering higher product quality and better production flexibility**
As part of its Sustainable Steel (SuSteel) project, the Austrian steelmaker voestalpine has built a small pilot hydrogen plasma reduction reactor at its Donawitz site.	

2.9.5 Suspension ironmaking

The process begins with the ultrafine grinding of low-grade iron ore to produce iron ore concentrate (Figure 28). This is then reduced using hydrogen in a high-temperature "flash" reactor for just a few seconds, directly producing steel once carbon is added. The iron ore concentrate can also be pre-reduced at a lower temperature in a separate reactor before being added to the flash reactor [1].

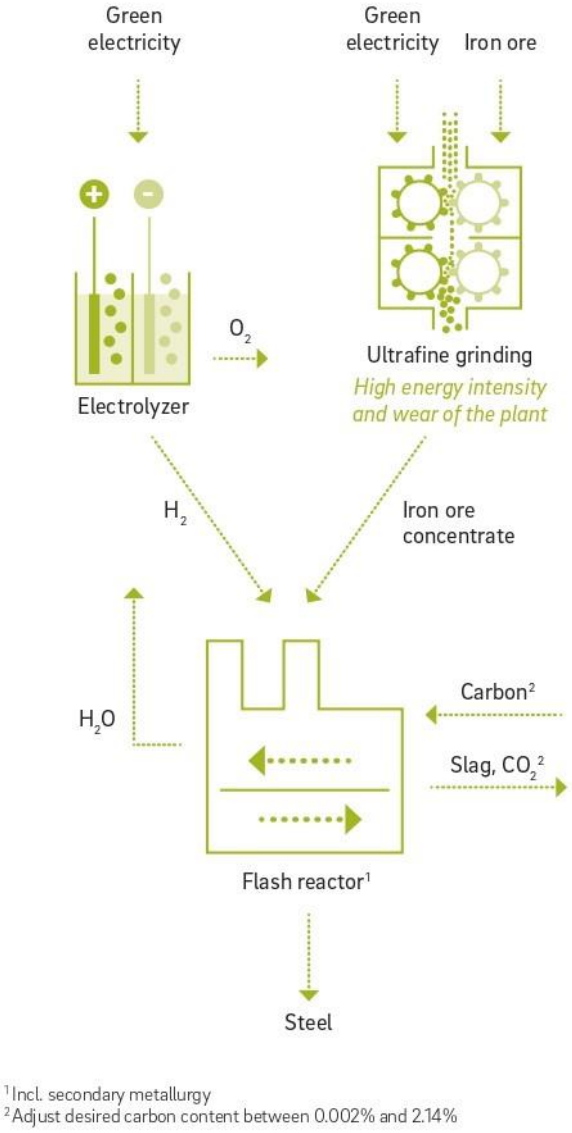


Figure 28 – Proposed suspension ironmaking. Source: [1].

Table 14 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on the use of H_2 in the direct reduction of iron in a shaft furnace.

Table 14 – Suspension ironmaking. Source: [1].

Pros	Cons
+ **The direct reduction of iron ore to steel in one reactor, removing the need for ironmaking, sintering or pelletization, has significant cost and emission benefits**	- The technology is not well developed and is still at an experimental stage, with no large-scale reactor tests yet conducted - As a result, the process is a long way from commercialization and will require significant investment

+	**It also produces "cleaner" steel as the high temperatures and fast reaction times ensure fewer impurities**	-	From a practical point of view, the iron ore must be ground to particles of <100 micrometers in diameter, requiring high energy intensity and increased plant maintenance
The University of Utah in the USA has conducted proof-of-concept tests in laboratory reactors and is developing the process and reactor design for industrial use			

2.9.6 Substituting H_2 for carbon as a reductant

Hydrogen could also be used directly as a reducing agent in the steel making process and therefore has excellent potential for CO_2 reduction. Many steel producers are trying to develop this option [4]. Decarbonization potential using hydrogen in the iron and steel industry is substantial. A simulation result indicates that the hydrogen-based direct reduction process can reduce up to 91% of direct CO_2 emissions relative to using natural gas. Moreover, hydrogen-based technologies are a representative cross-cutting option for decarbonization. It is, however, noticeable that the hydrogen production routes have a diverse nature, such as green, blue, and grey, and their carbon intensities are also widely ranged.

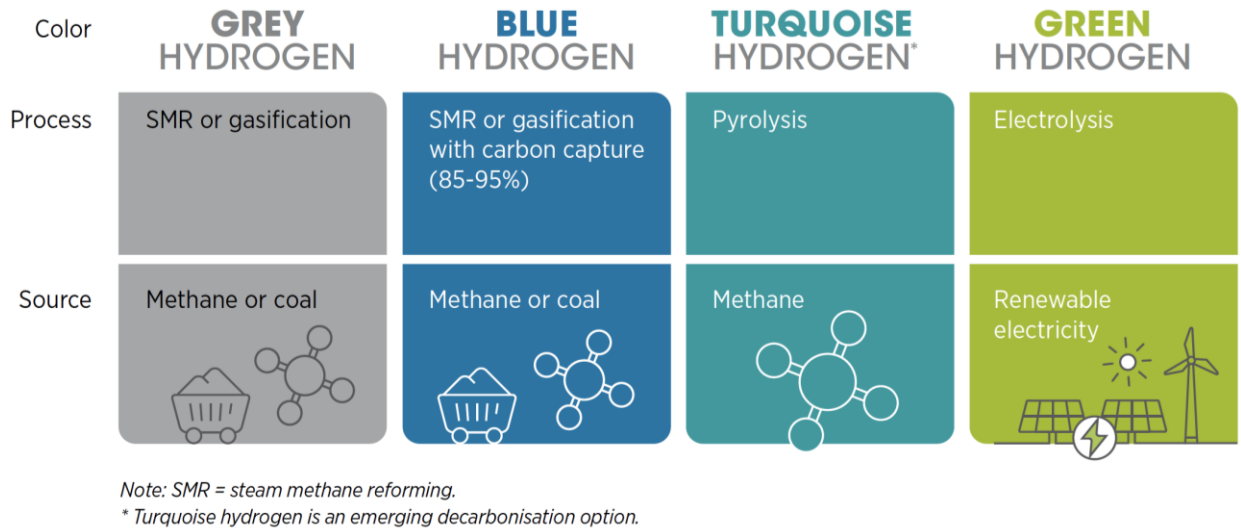


Figure 29 – Selected shades of hydrogen. Source: [37].

Thus, the decarbonization of the iron and steel industry via hydrogen must besupported by the hydrogen produced from a low-carbon route. Sintering is the second largest energy-consuming process in the iron and steel industry. Thus, it is quite natural that there have been continuous efforts to decarbonize sintering, and energy saving by process optimization is one of those efforts. Process

optimization by integrating a hybrid just-in-time learning soft sensor and thermodynamic optimization could be applied for saving energy during the sintering process.

Direct reduction of iron is the chemical removal (reduction) of oxygen from iron ore in its solid form. The iron used in the steelmaking process is currently chemically reduced from iron ore through the use of fossil resources – natural gas or coal. This process is known as Direct Reduced Ironmaking (DRI). Carbon combines with the oxygen in the iron ore, producing metallic iron and a carbon-rich process gas, according to the following simplified chemical reaction [38]:

$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$

Currently, for every tonne of iron that is produced from iron ore, on average 2.21 tonnes of CO_2 is emitted. It is also possible to reduce iron ore using hydrogen instead of carbon; in this case the waste gas produced is water, as per the following reactions [38]:

$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$, $FeO + H_2 \rightarrow Fe + H_2O$

In natural gas-based DRI production, hydrogen does play a role in the reduction process, though this is in combination with carbon. Greenhouse gas (GHG) emissions from gas-based DRI production are lower than from the BF route, with every tonne of DRI produced leading to the emission of 1.5 tonnes of CO_2. Pure hydrogen is not currently used in ironmaking applications [38].

There are three main sources of hydrogen. ‘Green’ hydrogen is produced by combining renewable energy with electrolysis, ‘blue’ hydrogen is produced from fossil fuels in a facility equipped with carbon capture and storage (CCS), an ‘grey’ hydrogen comes from unabated fossil fuel. In its 2020 technology roadmap, the International Energy Agency (IEA) suggests that under its ‘Sustainable Development Scenario’ (SDS) scenario, green hydrogen is introduced as a primary reducing agent at a commercial scale in the mid-2030s. Use expands to 12 Mt per year by 2050. While this represents a fast scale up and deployment of a new technology, the IEA’s modelling suggests that by 2050 under 8% of total steel production will rely on electrolytic hydrogen as the primary reducing agent (or 14% of primary production) [38].

Examples of blue hydrogen production include Shell’s Quest project and Air Products’ Port Arthur facility. The largest electrolyser in the world is currently a 10 megawatts (MW) unit located in Japan, capable of producing 1,200 Nm3 of hydrogen per hour. A plant with a capacity of 100 MW is to be built in the Port of Hamburg [38].

Steel companies are currently looking at hydrogen use in a number of ways. The first approach is to develop and deploy breakthrough hydrogen reduction technology, virtually eliminating direct GHG emissions from the ironmaking process. A number of steelmakers are taking this approach; key



projects include Hybrit (SSAB/LKAB/Vattenfall) and ArcelorMittal's Hamburg pilot project. The IEA views hydrogen reduction as being very important for net-zero emission, and at technology readiness level (TRL) 5, likely to be available from 2030 [38].

Another group of steelmakers are looking at the transitional use of hydrogen by blending it with fossil-based reductants, using it in conventional steelmaking processes (BF and DRI) to improve greenhouse gas efficiency. ThyssenKrupp is testing the use of hydrogen in a blast furnace; this approach has also been studied in Japan as part of the COURSE50 project. The approach is rated by IEA at TRL 7, ready for deployment in 2025 [38].

Tenova, Salzgitter and thyssenkrupp have or are testing natural gas-based DRI with high levels of hydrogen blending (TRL 7, 2030). Voestalpine's SuSteel project is looking to apply hydrogen plasma reduction to ironmaking, while the University of Utah is researching flash ironmaking technology (TRL 4). Hydrogen can also be used in ancillary processes, such a reheating furnace, as a substitute for natural gas [38].

2.9.6.1 H_2-based direct reduced iron-shaft furnace

Instead of a carbon reductant such as coke, H_2 is used to reduce iron ore pellets to "direct reduced iron" (DRI, or sponge iron). The reaction takes place in a shaft furnace, a type of furnace that uses gas reductants to make DRI (Figure 30). The operating temperature can be fairly low, around 800°C. The DRI is then fed into an EAF and turned into steel by further processing it and adding carbon. As an interim technology to pave the way towards carbon-neutral steelmaking, it can also be fed into a blast furnace in the form of "hot briquetted iron" (HBI), a high quality DRI. This significantly increases the blast furnace efficiency and reduces coke usage. The most common processes are the MIDREX method and Tenova's HYL [1].



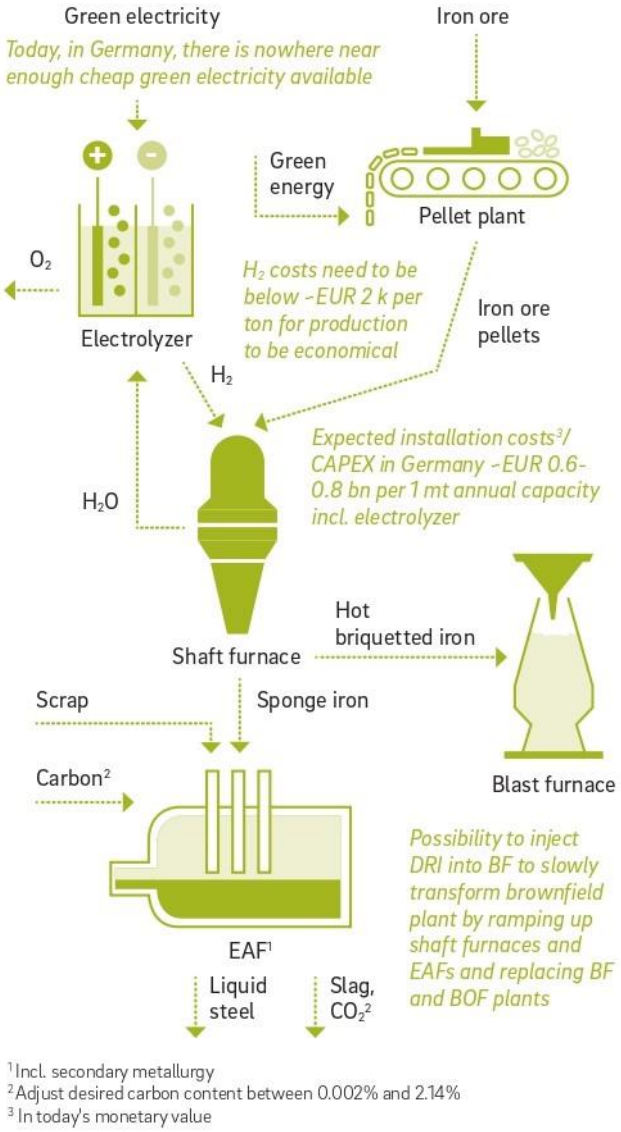


Figure 30 – Proposed H_2-based direct reduced iron – Shaft furnace. Source: [1].

Table 15 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on the use of H_2 in the direct reduction of iron in a shaft furnace.

Table 15 – H_2-based direct reduced iron – shaft furnace. Source: [1].

Pros		Cons	
+	**If powered solely by green electricity, the process makes the whole primary steelmaking route carbon neutral and fossil fuel-free**	-	The process still requires iron ore pellets, and producing them can cause significant emissions depending on the heat source of the pellet plant
+	**Other benefits include high production flexibility: the process is easy to start**	-	Supplying the necessary amount of H_2 is also a problem and efficient large-scale

	and stop, and the ability to use smaller units enables greater scalability		electrolyzers need to be developed
+	**In addition, the ability to feed DRI as "hot briquetted iron" into a blast furnace (BF)-basic oxygen furnace (BOF) system means existing conventional brownfield plants can be used while shaft furnace/electric arc furnace (EAF) production is ramped up**	-	As the process relies on vast amounts of cheap green energy, steel producing countries must import H_2 or pre-processed iron, hurting their value chains, if they fail to significantly ramp up their own green energy production
		-	There is also uncertainty around future operating costs, for example relating to H_2 and electricity prices

Example of pilot project:

+The EU-funded Project GrInHy 2.0, which involves several firms including Tenova, Salzgitter and Paul Wurth, aims to develop the world's largest H_2-producing steam electrolyzer for use in MIDREX and HYL

2.9.6.2 H_2-based direct reduced iron-fluidized bed

As with the shaft furnace version, this method uses H_2 to reduce iron ore and produce DRI to feed into an EAF. The differences are that reduction occurs in a fluidized bed rather than a furnace, and finely processed iron ore powders (fines) are used instead of pellets (Figure 31). Fluidized beds are reactor chambers that can continuously mix solid feedstocks with a gas to produce a solid. There are several possible processes, including FINEX and Circored [1].

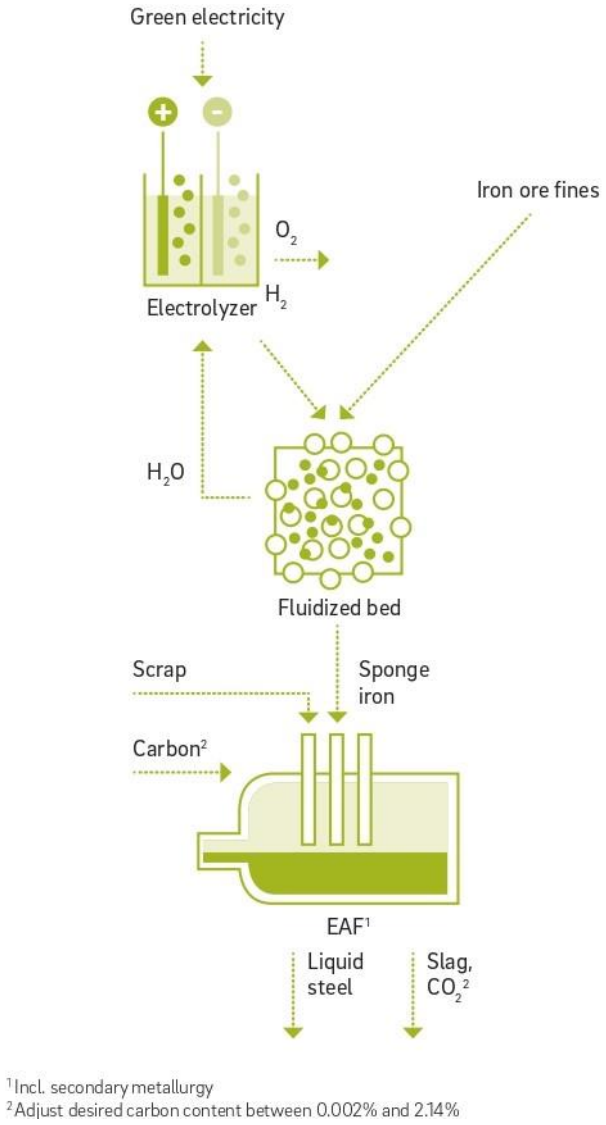


Figure 31 – Proposed H_2-based direct reduced iron – fluidized bed. Source: [1].

Table 16 shows the vision of the German consultancy Roland Berger on the decarbonisation option for the steel industry based on the use of H_2 in the direct reduction of iron in a shaft furnace.

Table 16 – H_2-based direct reduced iron – fluidized bed. Source: [1].

Pros	Cons
+ **The use of fines over iron pellets has the advantage of removing the need to pelletize, cutting costs and the high CO_2 emissions involved in the process**	- The process shares the same H_2 supply, electrolyzer and operating cost problems as the shaft furnace method - Its electricity supply must also be 100% green to achieve carbon neutrality - The use of fluidized bed reactors in steelmaking is less developed than shaft

+ **Fluidized bed reactors have fewer internal sticking problems than shaft furnaces, achieving higher metallization (approx. 95% to 90%)**	furnaces, requiring higher investment
Example of pilot project: *+Outokumpu, the Finland-based stainless-steel producer, began production of an H_2-DRI plant using the Circored process in Trinidad and Tobago in 1999* *+ It could produce up to 65 tons per hour of hot briquetted iron* *- Today, it is owned by ArcelorMittal and has been inactive since 2015*	

2.9.7 Challenges foreseen by the use of H_2, CCS, electrolysis and biomass in the steel sector

Table 17 shows the vision of the World Steel Association AISBL on the challenges foreseen by the use of H_2, CCS, electrolysis and biomass in the steel sector.

Table 17 - Challenges foreseen by the use of H_2, CCS, electrolysis and biomass in the steel sector. Source: [31][32][33][35][38].

Technological innovation foreseen for the decarbonisation of the EU steel industry			
Hydrogen	**CCS technologies**	**Electrolysis**	**Biomass**
Scale up: -Commercial e-H_2 as a primary reducing agent Available in the mid-2030s -By 2050 the greatest demand for e-H_2 in steel in India and China -All current H_2 use will require 3600 TWh	Scale up: -By 2020 75% of all the CO_2 produced globally in iron and steel can be captured -14 steel plants operating with 15 Gt CO_2 capture capacity need to be built every year from 2030 to 2070	Scale up: -In 2020 >1,8 Mt of steel was produced -Typical BF capable of making > 2.5 Mt iron/ year -Today: kilogrammes of iron have been manufactured using electrolysis	Scale up: -Robust supply chains are required to move the large amounts of biomass

	-Current < 0.001 Gt/year		
Cost: -Innovative process routes could cost 10-50% more -Cost of H_2 could fall 30% by 2030 as a result renewables and scaling up	Cost: -Innovative process routes could cost 10-50% more	-8 orders of magnitude are required -By 2050: IEA modelling suggests that 100 Mt of iron ore electrolysis can be produced	
Infrastructure: -Specialised infrastructure may need to be developed to enable distribution at scale -Existing NG transmission pipes could be converted to deliver pure H_2 in the future -The suitability must be assessed on a case by-case basis -3 times more volume is needed to supply the same amount of energy as NG -H_2O stressed areas: 9 L H_20 → 1 Kg H_2 + 8 kg O_2	Infrastructure: -Transport of CO_2 from point sources to sites established for large-scale offshore storage - Pipelines: their viability depends on access to land, the CO_2 volume and source origin -Dedicated sea tankers for transportation	Metallurgy: -Electrolysed iron will be 100% Fe -It represents a 'blank canvas', and alloying elements (including carbon) will need to be added to it to achieve the desired properties Electrodes: -Revolutionary aluminium smelting technology innovation by Alcoa that emits O_2 and eliminates GHG -Problems that need to be still solved are the development of a cheap, carbon-free inert anode that is resistant to the corrosive conditions in molten oxide	Supply chain: -Transportation and processing will also generate greenhouse gas emissions -LCA approach required to the assessment of emissions for the use of biomass in steel production

		electrolysis Flexibility: -Like an EAF, but unlike a BF, electrolysis-based production can be more easily scaled up and down	
Safety: -H_2 is so small it can diffuse -H_2 can also lead to cracking in steel pipes and vessels	Regulatory issues: -Still under development -No framework in the EU to quantify and verify the CO_2 stored -Not universally embraced Public acceptance: -Acceptance remains a bottleneck for its broad deployment -NGOs dismiss CCS as high risk, unproven and fundamentally unnecessary -Local communities cite concerns around safety and impact on property value	Energy availability -Significant increase in low-carbon electricity generation capacity would be required -A 100 Mt would need to be supported by 46GW of electricity -Equivalent to 5500 wind turbines or 28 1.6 GW nuclear reactors	Sustainability & Land Use: -Increasing demand for bioenergy feedstock is leading to conflicts -Competition for arable lands required for food and fibre production -Soil disturbance, nutrient depletion and impaired water quality



2.10 Emerging breakthroughs and transformative innovations

Table 18 shows possibly transformative options for the near future: i) commercially available but not yet widely diffused (as of 2020); ii) emerging soon with working prototypes; and iii) those at the experimental and likely only after 2025. Interestingly, more innovations are commercially available (45) than are both emerging (17) or in experimental stages (24) according to the original source pf the information [4].

Table 18 - Commercially available, emerging, and experimental innovations for the iron and steel industry. Source: [4].



Level of sociotechnical system	Commercially available but not yet widely utilized (as of 2020)	Emerging soon with working prototypes (as of 2020)	Experimental and likely only after 2025
Raw materials	1. Solid recovered fuels for use as reducing agents 2. Heat recovery from sinter cooler 3. Single-chamber-system coking reactors	1. Primary Energy Melter	1. Low-carbon hydrogen-based direct reduction 2. Charcoal in the sintering process 3. Torrefied biomass
Iron and steel making	4. Use of recuperative burners 5. Replacing existing equipment with more efficient ovens, burners, kilns, and furnaces 6. Process modification of kilns 7. Optimization of furnace 8. Waste heat recovery 9. Use of ceramic ladles instead of cast iron pipes 10. Efficient ladle preheating 11. Radiation recuperators for ladle furnace 12. Coal moisture control 13. Coke dry quenching 14. Injection of pulverized coal 15. Top-pressure recovery turbines 16. Recovery of BF/BOF gas 17. Charging carbon composite agglomerates	2. Advanced control of heating walls in coke ovens 3. Hot oxygen injection 4. Tecnored 5. Cyclone converter furnace 6. Continuous horizontal sidewall scrap charging 7. Converting off-gases to fuels (BF) 8. Converting off-gases to chemicals (BF)	4. Plasma blast furnace 5. Off-gas hydrogen enrichment (BF) 6. CO_2 removal for use or storage (BF) 7. Electrolytic H_2 blending (BF) 8. Natural gas-based DRI with high levels of low or zero-carbon electrolytic H_2 blending 9. Natural gas-based DRI with CO_2 capture 10. DRI based solely on low or zero-carbon electrolytic H_2 11. Paired straight hearth furnace 12. Molten oxide electrolysis 13. Suspension hydrogen reduction of iron oxide concentrate 14. Ironmaking using biomass and waste oxides 15. New scrap-based steelmaking process 16. In-situ real-time measurement of melt constituents 17. Continuous steelmaking for EAF
Steel products making and usage	18. Near net shape casting (thin slab) 19. Bottom stirring/stirring gas injection 20. Use of foamy slag practices 21. Use of oxy fuel burners 22. DC arc furnace 23. Scrap preheating and continuous charging 24. Flue gas monitoring and control 25. Eccentric bottom tapping 26. Improved process control 27. Ultra-high-power transformer 28. Twin shell furnace 29. Hot charging 30. Recuperative or regenerative burner 31. Use of ceramic low thermal mass insulators for reheating furnace 32. Controlling oxygen level and variable speed drive on combustion air fans 33. Efficient drives in rolling mill and machining 34. Waste heat recovery (cooling water, annealing, and compressor) 35. Reduced steam use for pickling 36. Automated monitoring and targeting systems 37. Thermal insulation for plating bath 38. Automated bath cover 39. Compressed air network modification 40. Reducing air extraction across heating solution 41. Efficient compressors 42. Optimizing the process solution temperature 43. Use of high-strength steel	9. Energy monitoring and management system in casting 10. Preventative maintenance in steel mills or EAF plants 11. Variable speed drives for flue gas control, pumps, fans in integrated steel mills 12. Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills 13. Additive manufacturing	18. Smelting reduction with CCUS 19. low or zero-carbon H_2 for high-temperature heat (ancillary processes) 20. Next-generation system for scale-free steel reheating 21. Thermochemical recuperation for steel reheating furnaces 22. Oxygen-rich furnace System 23. Integrating steel production with mineral sequestration
Waste and recycling	44. Rotary hearth furnace dust recycling system 45. Injection of plastic waste	14. Recycling basic oxygen furnace slag 15. Recycling of stainless steel dust 16. Regeneration of hydrochloric acid pickling liquor 17. Recycling of waste oxides in steelmaking furnace	24. Geological sequestration of carbon dioxide using slags

Note to Table 18: Detailed description of each innovation can be found elsewhere [4].



2.11 Barriers and risks facing the decarbonization of the steel sector

Although there are many options for the decarbonization of the steel industry, some barriers (any factor impeding technology adoption) and risks (any negative outcome to technology adoption) prevent their achievement as can be seen in Table 19 [4].

Table 19 – Barriers and risks facing the decarbonization of the steel industry. Source [4].

A	• Difficulty to justify large upfront capital costs for decarbonization projects that have limited deployment and proven operational data. • Difficulty to integrate decarbonisation efforts into steel operations when sites and projects are being initially built and developed due to long life-cycles of steel plants. • Difficulty to accommodate new technologies without widely accepted carbon costs in retrofitting processes. • A low-carbon steel market that males difficult to justify increased operational costs.
B	• Difficulties in sharing innovations and best practices. • The capital intensive and oligopolistic nature of the iron and steel sector hinders the low-carbon transformation of the industry. • Uncertainty and risks also prevent an active investment for decarbonization.
C	• Steel products are durable—have a relatively long lifetime relative to other consumer goods. We may wait a hundred years or more to recycle or replace the steel in buildings, bridges, and infrastructure. • Recycling, replacement, and secondary steel naturally have a time lag and hence are limited in their ability to serve as decarbonization options, although they have significant overall potential.
D	• There has been little attention to developing effective financing and business models for decarbonization since big players have enough capital to invest if the measures and innovations offer attractive returns. • There is a need for policy instruments to overcome the barriers and harness the dissemination of innovative, cross-cutting options for the industry's low-carbon future. • Carbon taxes and regulatory standards could also be an effective measure for the decarbonization of the iron and steel industry. • Border-tariff adjustments could minimize the risks of leakage and give a signal to other sectors, resulting in the price increase of carbon-intensive imported goods. • Increasing R&D subsidies for energy-saving and climate-friendly technologies and encouraging the



	diffusion of advanced equipment and technologies.

A) Financial and economic barriers; **B)** Organizational and managerial barriers; **C)** Behavioral barriers; and **D)** Policy instruments.

3 Conclusions

The European sector is under pressure due to its CO_2 emissions produced by its high energy and resource intensive processes. The sector contributes to approximately 4% of total European CO_2 emissions and to 22% of total EU industrial emissions. Steel in Europe is mainly produced by two routes. The primary route involves the processing of iron ore to produce iron sinter or pellets, and the melting these in a blast furnace with coke to make pig iron. This is processes in a basic oxygen furnace to create steel. The rest of the steel produced in Europe comes from the secondary route where stell is produced from scrap metal by heating it in an electric arc furnace. While the primary route emits mainly direct greenhouse gases, the secondary route emits mainly indirect greenhouse gases, which depend on the electricity mix used in the electric arc furnace. In consequence, the primary route is the main target to reduce emissions in the sector. In 2020, the steel sector in Europe reported that the industry supported more than 2.6 million total full time equivalent jobs. Crude steel production for 2020 was 139 million tonnes. The Gross Value Added of the European steel industry was €132 billion if direct, indirect and induced effects are factored. The EU sector consumed around 0.84 EJ of energy in 2020. Decarbonisation options are available for both EU routes of steel production. The primary route as the highest CO_2 emitter, is the main target to lower emissions. Methods such as coke dry quenching and optimizing pellet ratios, as well as BF equipment like top gas recovery turbines, reduce conventional primary route carbon emissions. Replacing coke with biomass and natural gas with hydrogen can also significantly cut CO_2 in primary steelmaking, as can injecting hydrogen or ammonia into the BF to partly replace pulverized coal. These technologies will still require development in the following years. Lower secondary route emissions can be achieved by making savings on the electricity used to power the EAF, or shifting the electricity mix towards renewables. Many of the proposed solutions will require massive amounts of affordable green electricity – for iron ore pre-processing, H_2 electrolysers, furnaces and electrolysis – to meet the carbon neutrality goal. But such energy sources are far from meeting the required price points compared to coke (excl. carbon tax) and will take time to develop.



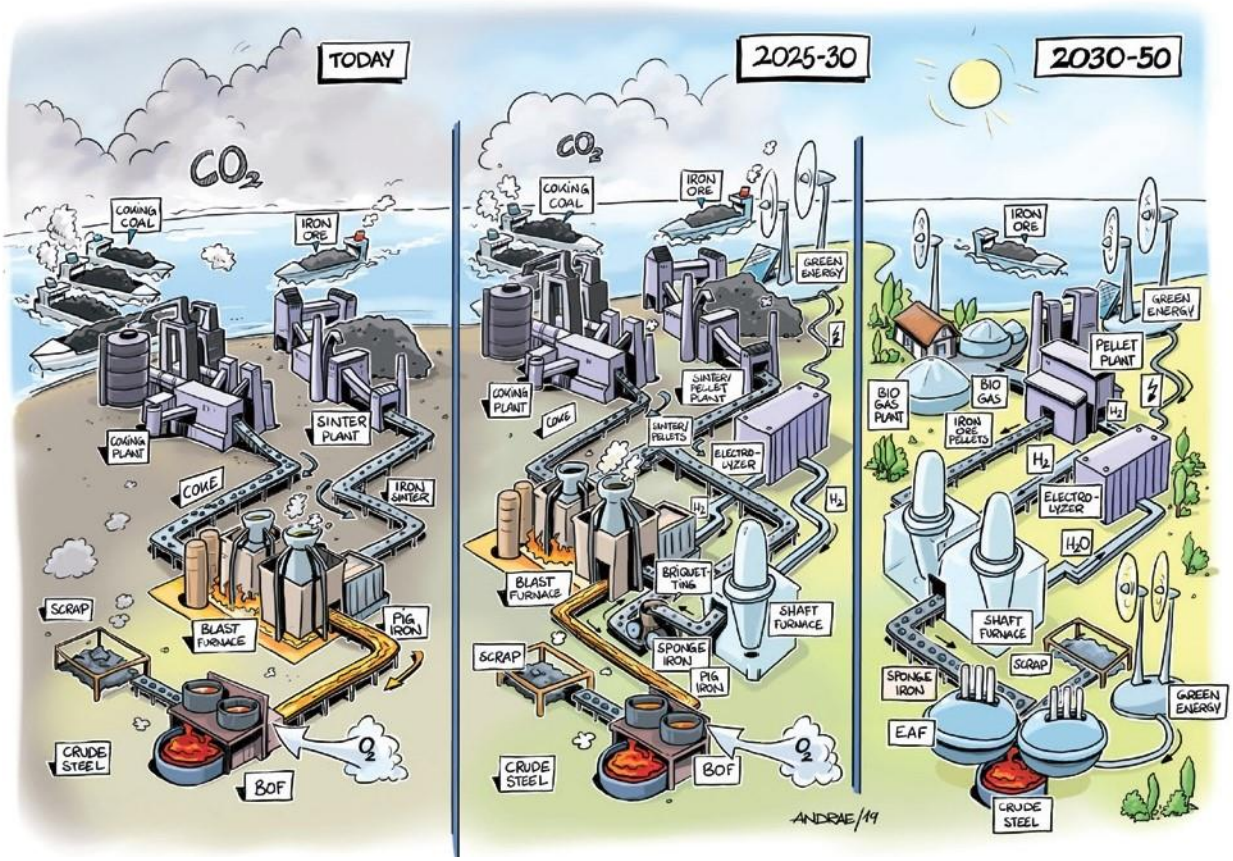


Figure 32 – How to transform a brownfield steel plant into an H_2-based DRI shaft furnace plant. Source: [1].

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100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

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Country Report – Germany

Author: Benedetta Di Costanzo, Rainer Janssen, Cosette Khawaja

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Abbreviations

Abbreviation	Definition
BMWK	Bundesministerium für Wirtschaft und Klimaschutz (German Federal Ministry for Economic Affairs and Climate Action)
BVK	Bundesverband der Deutschen Kalkindustrie e. V. (German Lime Association)
CCS	Carbon Capture Storage
CCU	Carbon Capture Utilisation
CDA	Carbon Direct Avoidance
CO_2	Carbon dioxide
EID	Energieintensiven Industrien in Deutschland (Energy Intensive Industries in Germany)
EII	Energy Intensive Industry
ETS	Emissions Trading System
EU	European Union
GDP	Gross Domestic Product
Mt	Megaton
SCC	Smart Carbon Capture
SCS	Smart Carbon Separation
TWh	Terawatt-hours
VCI	Verband der Chemischen Industrie (German Chemical Industry Association)
VDZ	Verein Deutscher Zementwerke e.V. (German Cement Association)
WVMetalle	Wirtschafts Vereinigung Metalle (German Non-ferrous Metals Association)



1 Introduction

The present report aims to provide an overview of the Energy Intensive Industries (EIIs) sector in Germany. The focus is on the RE4Industry target sectors, i.e. non-ferrous metals, lime, cement, chemicals & fertilizers, steel, ceramics, and glass. After a more general introduction on German EEIs, the report presents numbers and statistics on each industry sector, as well as their ongoing decarbonisation efforts and commitments towards GHG emissions reduction.

Even though Germany has by far the highest share of industrial production in the European Union[1] (EU), the energy intensity of its industrial sector is lower than the European average:

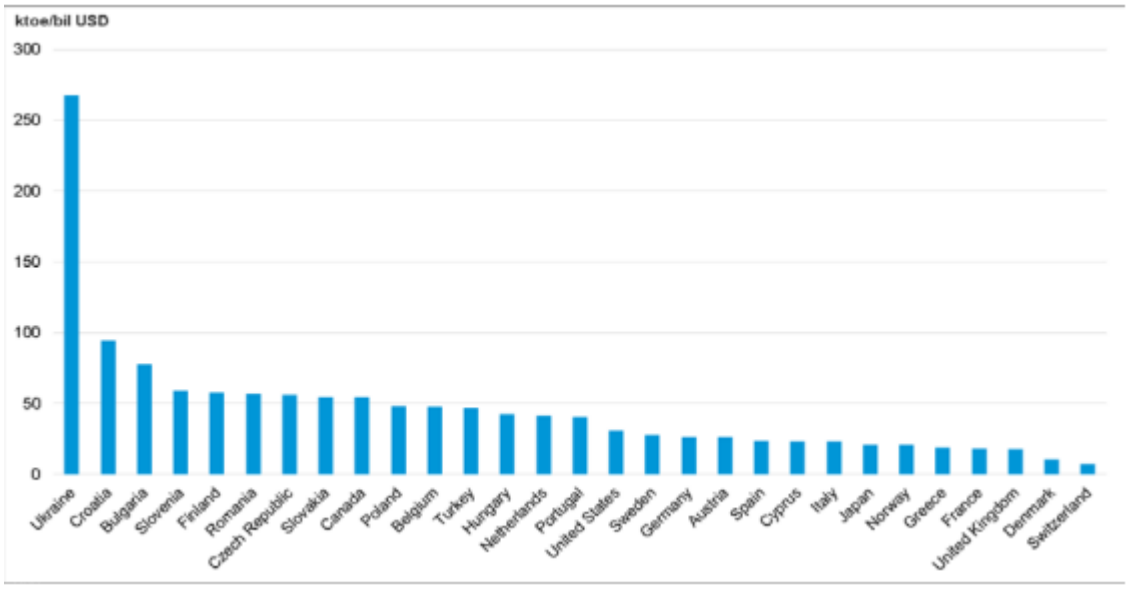


Figure 1 Industrial sector energy intensity for G7 and selected European nations (primary energy consumption/GDP). Source: Elizabeth Sendich, 2014, "Comparison of International Energy Intensities across the G7 and other parts of Europe, including Ukraine" (*https://www.eia.gov/workingpapers/pdf/international_energy_Intensity.pdf*)

German EEIs generate annual sales of around 330 billion euros (18% of the sales of the entire manufacturing industry)[2] and employ around 880,000 people, equivalent to 15% of the workforce in the manufacturing sector. Every job in energy-intensive basic production secures about two jobs in other branches of industry and in the service sector. That means that EEIs generate about 2.5 million jobs in Germany[3].

[1] In 2020 Germany recorded the highest value of sold industrial production, equivalent to 29% of the EU total, followed by Italy (18%) and France (12%). Source: Eurostat, 2021, "Industrial production statistics" (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_production_statistics#Industrial_production_by_country)

[2] Die Energieintensiven Industrien in Deutschland, "The energy-intensive industries ensure prosperity" (https://www.energieintensive.de/)

[3] Die Energieintensiven Industrien in Deutschland, "EID: Daten und Fakten" (https://www.energieintensive.de/die-industrien)

The EEIs in Germany spend more than 17 billion euros on energy every year, for a net electricity consumption of 525 TWh[4].

The figure below shows the distribution of the total emissions from individual industrial sectors. The iron and steel industry accounts for the largest share of industrial emissions at around 28%, followed by refineries (20%), cement clinker production (18%) and the chemical industry (15%).

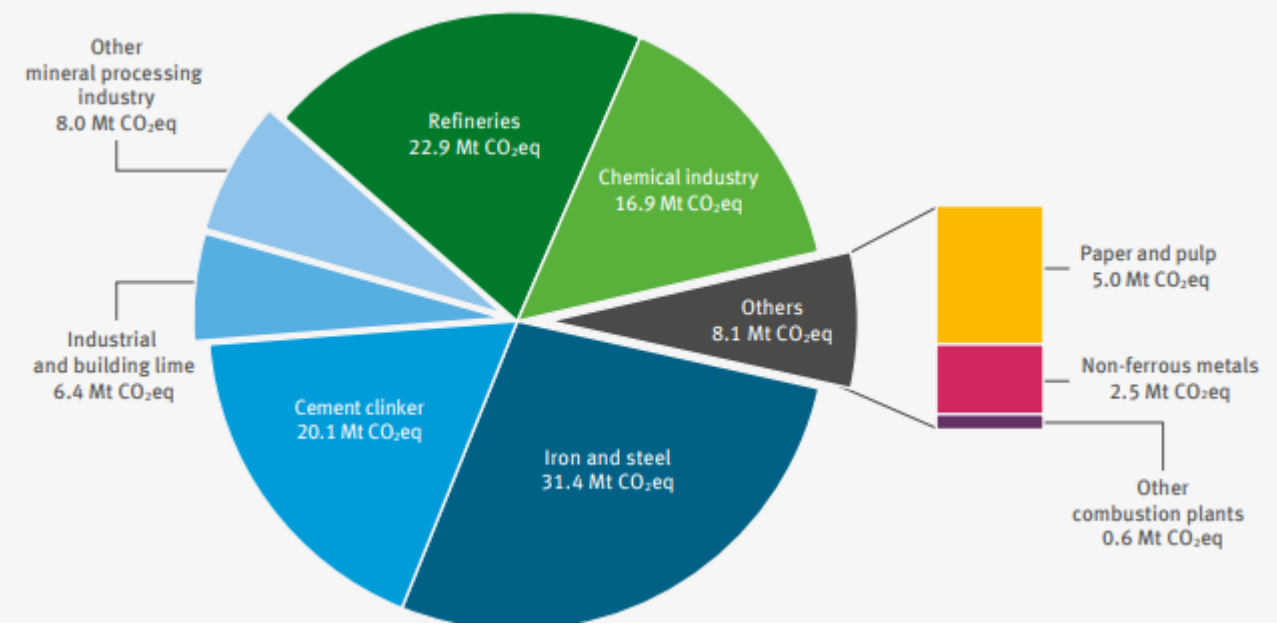


Figure 2 Distribution of emissions among individual industrial sectors in 2020. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Nevertheless, at the same time German EEIs invest heavily in energy-saving and emission-reducing production technologies. Between 1990 and 2012, they reduced their greenhouse gas emissions by a total of 31%, while increasing production by 42%[5] and in 2020 emissions fell in almost all sectors, sometimes considerably, compared to the previous year.

[4] *Ibidem.*
[5] *Ibidem.*

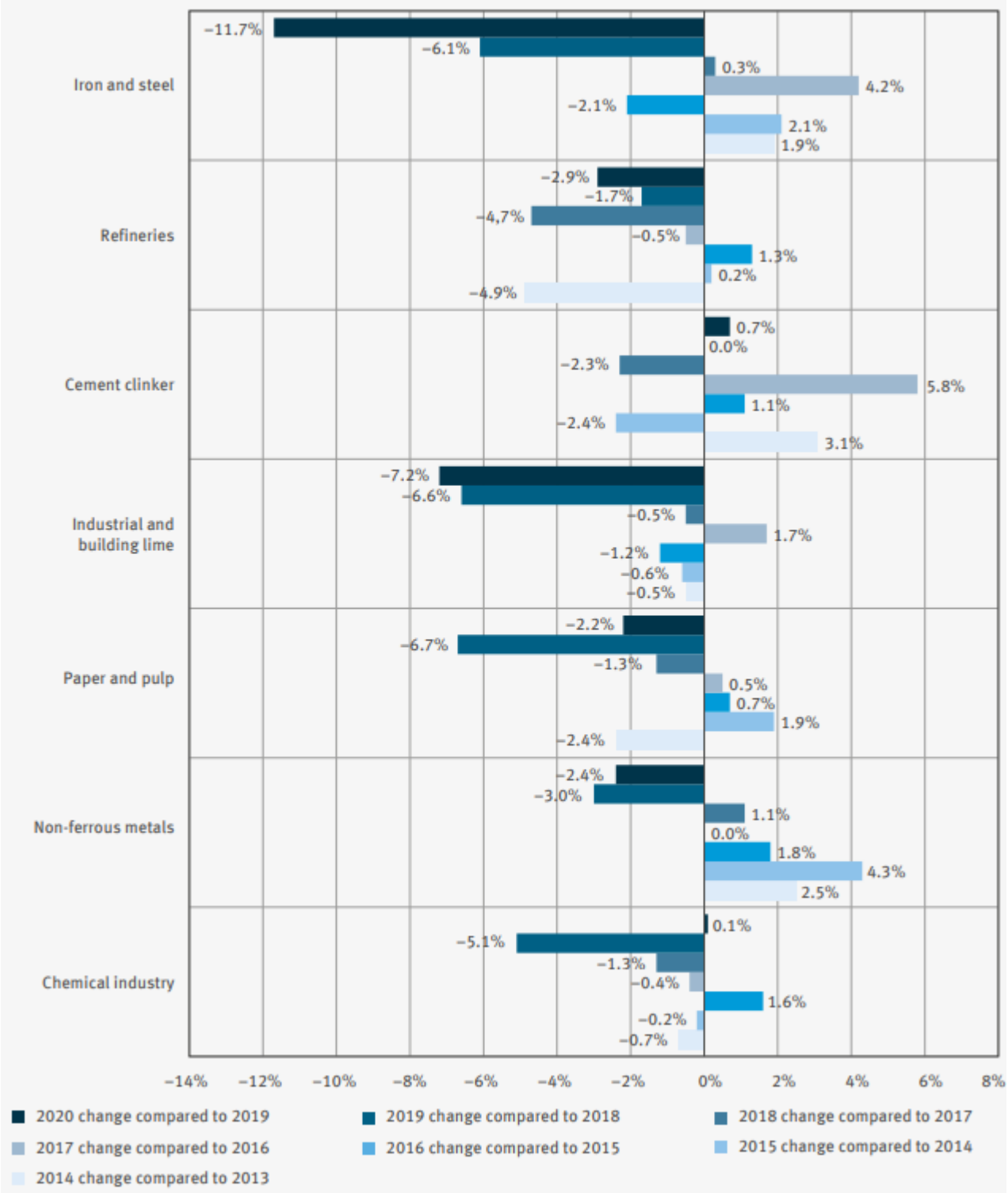


Figure 3 Annual emission changes in the industrial sectors since 2013. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (*https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3*)

EID – Die Energieintensiven Industrien in Deutschland

German EEIs joined forces under the umbrella of the EID[6], the platform for Energy Intensive Industries in Germany. Within the EID, the building materials, chemicals, glass, non-ferrous metals, paper and steel sectors bundle their common energy and climate policy positions. Other common themes are resource efficiency and environmental policy.

Members of the EID are the following:

- German Building Materials Association: Bundesverband Baustoffe - Steine und Erden e.V. (bbs)
- German Chemical Industry Association: Verband der Chemischen Industrie e.V. (VCI)
- German Glass Industry Association: Bundesverband Glasindustrie e.V. (BV Glas)
- German Metal Trade Association: WirtschaftsVereinigung Metalle. e.V. (WVMETALLE)
- German Paper Industry: DIE PAPIERINDUSTRIE e. V.
- German Steel Federation: Wirtschaftsvereinigung Stahl (WV Stahl)

[6] EID – Die Energieintensiven Industrien in Deutschland: https://www.energieintensive.de/

2 Non-ferrous metals

The non-ferrous metal industry is divided into light metal (aluminium and magnesium), non-ferrous metal (copper, zinc, lead, nickel and tin), and rare and precious metals. But the industry sector also refers to the different stages of the production process: from raw metal to semi-finished products (strips, sheets, rods, profiles, pipes and wires), to further processing, casting and hot-galvanising.

In Germany, there are 649 companies active in the non-ferrous metals sector, employing more than 108.000 workers and with a turnover of 53.2 billion euros (2020)[7].

The achievements of the German non-ferrous metal industry in 2020 were significantly affected by the COVID-19 crisis. In terms of production, on the one hand the companies producing and processing non-ferrous metals generated a total of 7.3 million tonnes in 2020 (a decrease by 7.7 percent compared to 2019). On the other hand, 2020 production was still above the level of the financial crisis year 2009 (when production was 6.7 million tonnes), but 14 percent lower than the most recent peak in production, occurred in 2017 (8.5 million tonnes). According to the forecasts, the non-ferrous metals industry is expected to not reach the pre-pandemic production level (i.e. of 2018) until 2022 at the earliest[8].

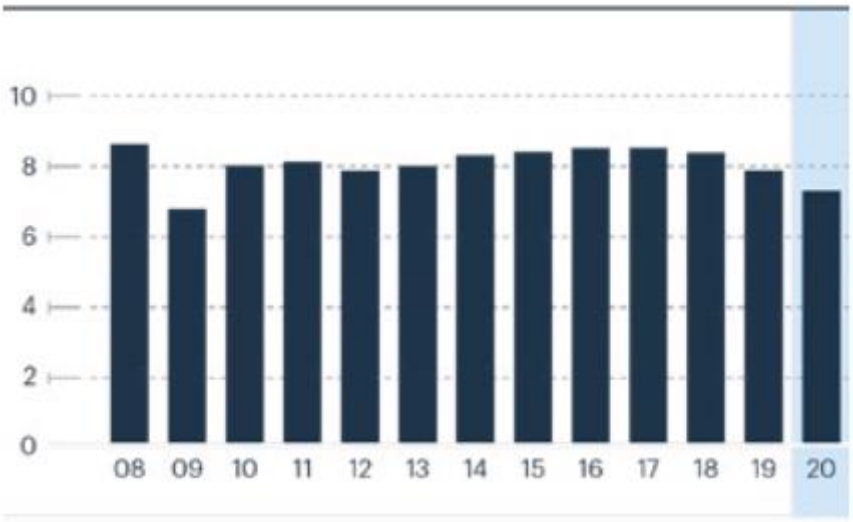


Figure 4 German non-ferrous metals industry production 2008-2020. Source: WVMetalle, 2021, "Gemeinsam Aufbrechend – Der Geschäftsbericht der Nichteisen-Metallindustrie" (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=282762&token=b83d45f6a5de8ba60c9bfde1e17e91a0851da87a)

The entire value chain (raw metal production, initial processing into semi-finished products and further processing) was affected by the crisis. The only sub-sector untouched by the crisis was the hot-galvanising industry – which in 2020 even achieved a slight increase in production volumes

[7] WVMetalle, 2021, "Gemeinsam Aufbrechend – Der Geschäftsbericht der Nichteisen-Metallindustrie" (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=282762&token=b83d45f6a5de8ba60c9bfde1e17e91a0851da87a)
[8] *Ibidem*.

compared to the previous year – thanks to the fact that its products are mainly used by the dynamic construction industry, which was not negatively impacted by the pandemic[9].

The non-ferrous metals industry provides materials and basic products for a whole range of other industries. The main end-user of non-ferrous metals in Germany is the automotive industry (automobiles, rail vehicles and aerospace), followed by the construction industry, electrical engineering and electronics industries, as well as mechanical and plant engineering. As shown in the graph below, the construction industry accounts for the use of 29% of the non-ferrous metals produced in Germany. Nevertheless, not even a strong and dynamic sector as this one was able to compensate for the declining demand from the other customer industries, during the Corona crisis in 2020[10].

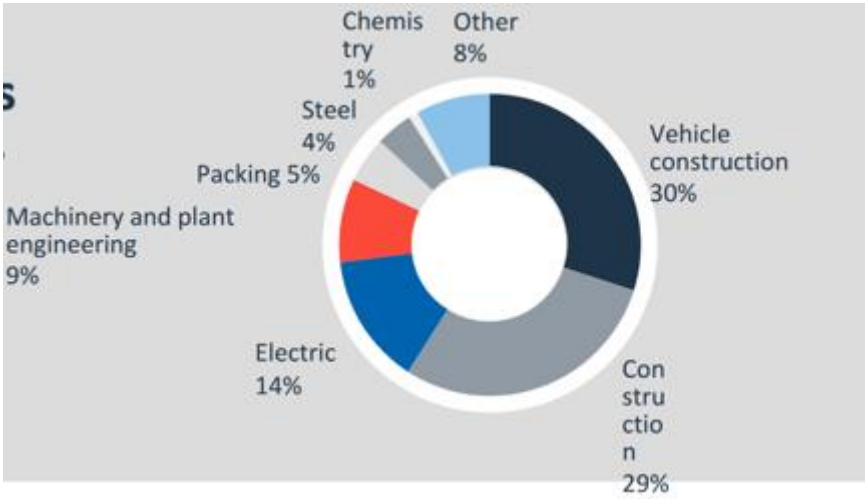


Figure 5 Non-ferrous metals industry customer industries. Source: WVMetalle, 2021, Metallstatistik – Gemeinsam Aufbrechen 2020“ (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=314715&token=ae6cf4b3bd20efc41f3d76bfb263e9af22798787)

As an energy-intensive industry, the non-ferrous metals sector has an energy use of 27.285 GWh (2020), with a specific energy input of 3.9 MWh per ton of material produced[11].

[9] *Ibidem*.
[10] *Ibidem*.
[11] WVMetalle, 2021, Metallstatistik – Gemeinsam Aufbrechen 2020“ (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=314715&token=ae6cf4b3bd20efc41f3d76bfb263e9af22798787)

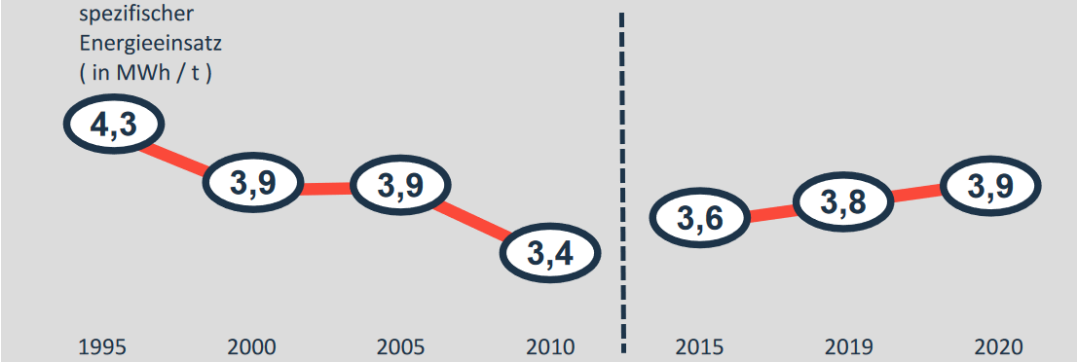


Figure 6 Specific energy input of German non-ferrous metals industry in 2020[12]. Source: WVMetalle, 2021, Metallstatistik – Gemeinsam Aufbrechen 2020" (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=314715&token=ae6cf4b3bd20efc41f3d76bfb263e9af22798787)

The German non-ferrous metals industry still heavily relies on fossil energy sources[13].

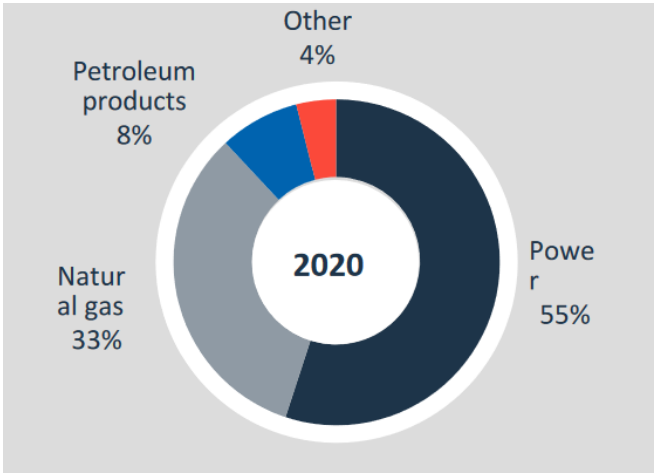


Figure 7 Type of energy used by the German non-ferrous metals industry. Source: WVMetalle, 2021, Metallstatistik – Gemeinsam Aufbrechen 2020" (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=314715&token=ae6cf4b3bd20efc41f3d76bfb263e9af22798787)

In 2020, installations in the non-ferrous metals industry emitted around 2.5 million tonnes of carbon dioxide equivalents in Germany, with a decrease of about 3 percent compared to the previous year (a similar decrease happened between 2018 and 2019). Aluminium-related activities are the most polluting ones, as shown in the graph below[14].

[12] The decisive factor for an increase in specific energy use in 2019 and 2020 compared to previous years was an automotive-related slump in demand for secondary aluminium. As a result, the share of more energy-intensive primary production increased.
Note: In 2015, the number of businesses reporting their energy use increased.
[13] *Ibidem*.

[14] German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-

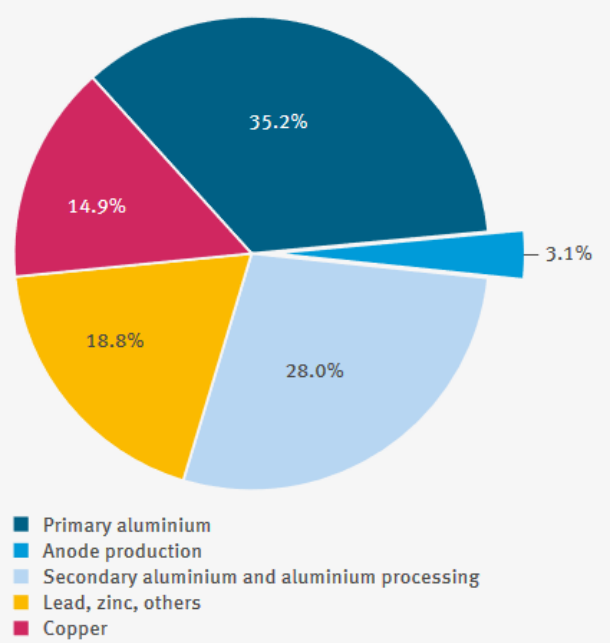


Figure 8 Shares of 2020 emissions from the non-ferrous metals industry. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Sustainability commitments

The non-ferrous metal industry makes a significant contribution to resource efficiency, particularly through the recycling of metals. The recycling rate of the German non-ferrous metals industry is the highest in an international comparison[15]. Non-ferrous metals can in fact be recycled as often as desired without any loss of quality. Recycling metals reduces the CO_2 footprint and thus helps to better achieve climate protection goals.

WVMetalle gave life to the "Metalle Pro Klima" Initiative[16] more than 10 years ago. The initiative encourages adhering companies to always strive in order to optimize their production processes in terms of energy and resource efficiency, and promotes best practice examples in the sector.

The non-ferrous metals industry is nevertheless facing the pressing concern of industry migrating from Germany to regions with lower climate protection goals. In order to ensure the thriving of the German non-ferrous metals industry, which also provides materials for many innovative green technologies, it is therefore key that the right balance is maintained between burdens and opportunities and close cooperation between the industry and policy-makers is therefore essential in this debate.

Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

[15] WVMetalle, 2021, "Gemeinsam Aufbrechend – Der Geschäftsbericht der Nichteisen-Metallindustrie" (https://www.wvmetalle.de/index.php?eID=dumpFile&t=f&f=282762&token=b83d45f6a5de8ba60c9bfde1e17e91a0851da87a)

[16] Metalle Pro Klima: https://metalleproklima.de/

3 Cement

There are currently 54 cement plants active in Germany, out of which 33 plants produce clinker. The sector employs almost 8.000 people and has a yearly turnover of over 3 billion euros[17].

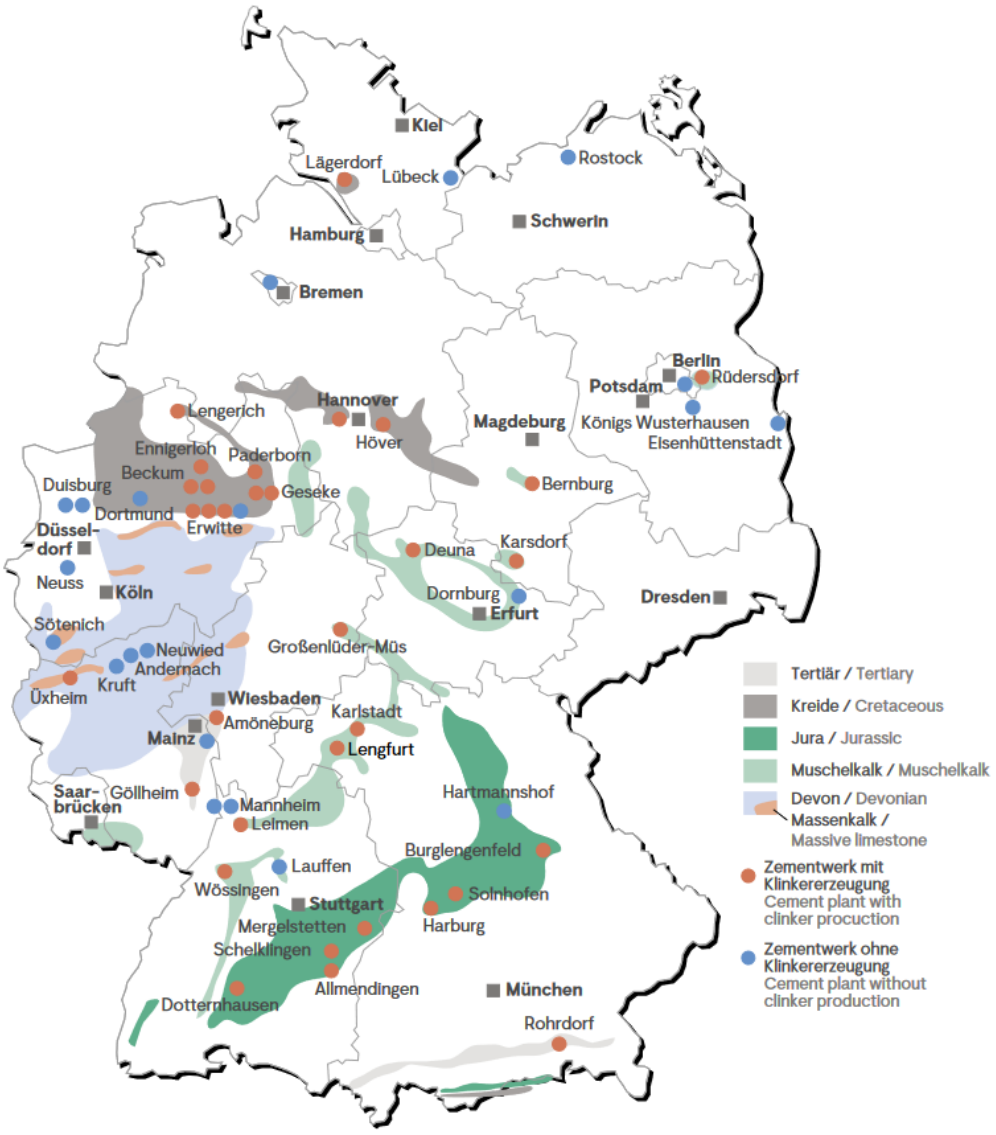


Figure 9 Cement plants in the Federal Republic of Germany in the year 2021. Source: VDZ, 2020, "Environmental Data of the German Cement Industry" (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/umweltschutz/Umweltdaten/VDZ-Umweltdaten_Environmental_Data_2020.pdf)

[17] VDZ, „Cement Industry in Germany" (https://www.vdz-online.de/zementindustrie/zahlen-und-daten/zementindustrie-in-deutschland)

Decarbonisation potential

The international cement industry is having to face up to the immense challenge of reducing its CO_2 emissions to an unprecedented extent. In Germany, cement manufacturers are responsible for 20 million tonnes of CO_2 emissions per annum, corresponding to 2% of the nationwide total[18]. CO_2 emissions from the cement sector are both raw material-related and energy-related.

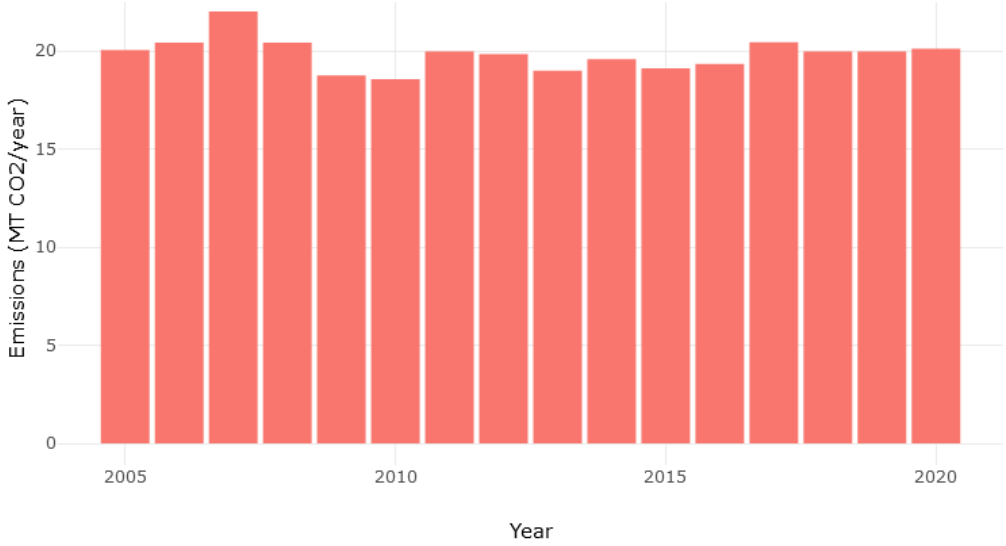


Figure 10 Emissions of cement industry in Germany 2005-2020. Source: Re4Industry, "EEIs Interactive Map" (https://re4industry.eu/eiis-interactive-map/)

On the one hand, raw material-related emissions are produced during limestone decarbonation and account for about 60% of direct CO_2 emissions of the sector[19]. Consequently, all the ambitions and potential cannot disguise the fact that “resource neutrality” is not going to happen. There will still be a need to use natural resources, albeit on a far smaller scale[20].

On the other hand, energy-related emissions are generated both directly through fuel combustion and indirectly through the use of electrical power.

Nevertheless, since 1990 German cement manufacturers have managed to reduce CO_2 emissions by 20-25%. Alongside improvements in the area of thermal efficiency, two factors in particular have been crucial to achieving this success: firstly, a reduction in the clinker content in cement, and secondly, a reduction in the use of fossil fuels, especially hard coal and lignite[21]. Nowadays, approximately 31% of the fuel energy consumption is covered by fossil, while the use of alternative fuels in the clinker burning process and alternative fuels in 2020 already accounted for 69.2% of the

[18] VDZ, 2020, “Environmental Data of the German Cement Industry” (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/umweltschutz/Umweltdaten/VDZ-Umweltdaten_Environmental_Data_2020.pdf)
[19] *Ibidem.*
[20] *Ibidem.*
[21] VDZ, 2020, “Decarbonising Cement and Concrete: A CO_2 Roadmap for the German cement industry – Executive Summary” (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/Executive_Summary_VDZ_Study_Decarbonising_Cement_and_Concrete_2020.pdf)

total fuel energy demand of the German cement industry[22] (by far above the EU average and highest share of alternative fuels in cement industry, in comparison with cement industries of other EU Member States[23]).

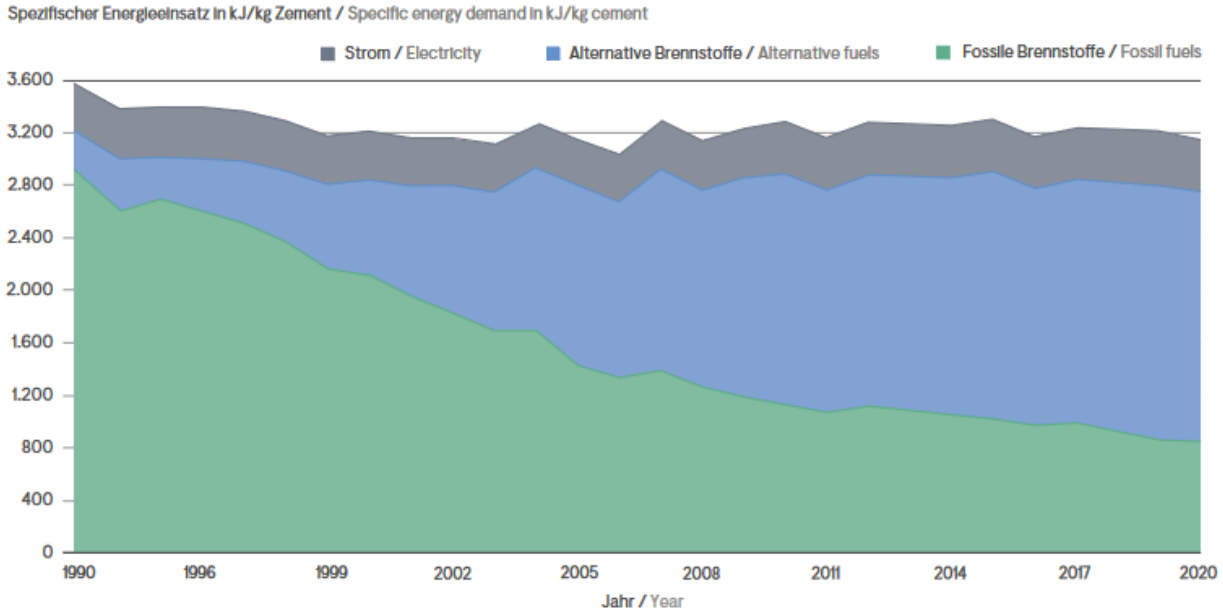


Figure 11 Development of the specific fuel energy consumption in the German cement industry. Source: VDZ, 2020, "Environmental Data of the German Cement Industry" (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/umweltschutz/Umweltdaten/VDZ-Umweltdaten_Environmental_Data_2020.pdf)

The cement industry is reaching the limits of its potential to further reduce CO_2 emissions, as in particular the process-related CO_2 emissions associated with clinker production cannot be lowered by employing conventional means. Efforts to fully decarbonise the sector will therefore have to rely heavily on carbon capture at the cement plant and its subsequent utilisation and storage (CCUS)[24]. The long-term goal must be to use the CO_2 which cannot be reduced in any other way by converting it into other substances and products.

VDZ describes pathways to the decarbonisation of cement and concrete up to the year 2050. Specifically, it develops two scenarios (the ambitious reference scenario, with a CO_2 reduction of 36% by 2050, and the climate neutrality scenario) which include state-of-the-art measures aimed at

[22] VDZ, 2020, "Environmental Data of the German Cement Industry" (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/umweltschutz/Umweltdaten/VDZ-Umweltdaten_Environmental_Data_2020.pdf)
[23] J. de Beer, J. Cihlar, I. Hensing, M. Zabeti, 2017, „Status and prospects of co-processing of waste in EU cement plants (http://www.cembureau.eu/media/rjqiyqca/2017-05-11_ecofys_publication_alternativefuels_report.pdf)
[24] VDZ, 2020, "Decarbonising Cement and Concrete: A CO_2 Roadmap for the German cement industry – Executive Summary" (https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/Executive_Summary_VDZ_Study_Decarbonising_Cement_and_Concrete_2020.pdf)

reducing direct CO_2 emissions of the German cement industry and of the cement and concrete value chain as a whole[25].

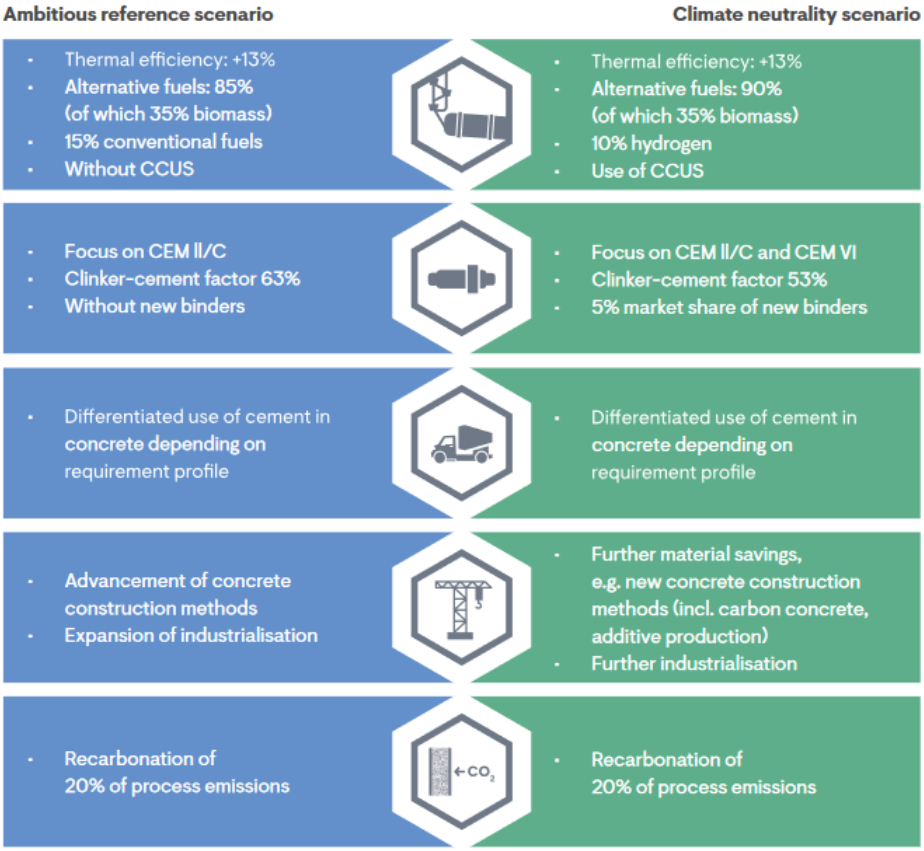


Figure 12 Assumptions on the technology mix for the cement industry in the scenarios up to 2050. Source: VDZ, 2020, "Decarbonising Cement and Concrete: A CO_2 Roadmap for the German cement industry – Executive Summary"
(https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/Executive_Summary_VDZ_Study_Decarbonising_Cement_and_Concrete_2020.pdf)

[25] *Ibidem.*

4 Lime

The lime industry is an indispensable raw material at the beginning of many value chains. In Germany, around 50 companies with over 100 lime burning plants and with around 3,000 employees produce ca. 6 million tons of lime every year, generating a total turnover of around 750 million euros (as of 2020)[26].

Around 2.3 million tons of lime are needed annually in the iron and steel industry; 1.2 million tons flow into environmental protection, 1.3 million tons of lime into the construction industry. Approximately 0.8 million tons are used in the chemical industry and other industrial applications as well as in agriculture. The rest is exported (as of 2018)[27].

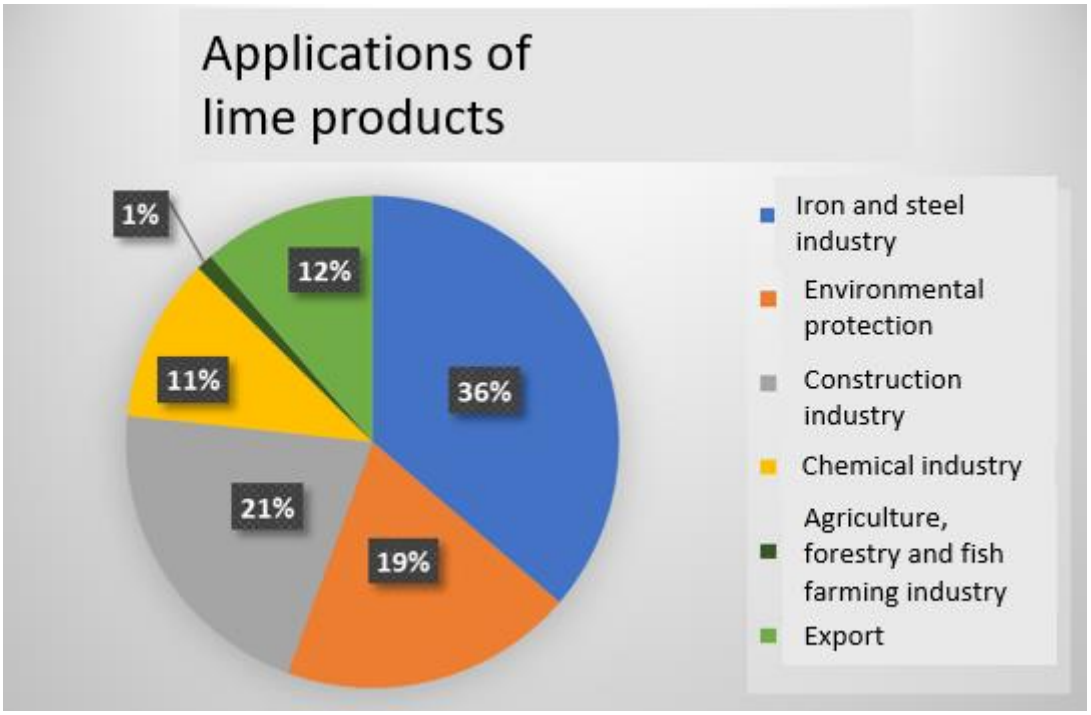


Figure 13 Areas of application of lime production. Source: Bundesverband der Deutschen Kalkindustrie e. V. (BVK), „Die Branche“ (https://www.kalk.de/verband/die-branche)

Decarbonisation commitments

Currently, the German lime industry emits more than 6.3 Mt of CO_2 per year and despite the use of more efficient kilns, the specific emissions have remained largely unchanged in recent years because more pulverised lignite was used as a fuel[28], but the German Lime Association (BVK) is

[26] Bundesverband der Deutschen Kalkindustrie e. V. (BVK), „Die Branche“ (https://www.kalk.de/verband/die-branche)
[27] *Ibidem*.
[28] German Emissions Trading Authority (DEHSt), 2021, “Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)”

strongly committed to a climate-neutral production of lime by 2050 through decarbonisation of their products[29].

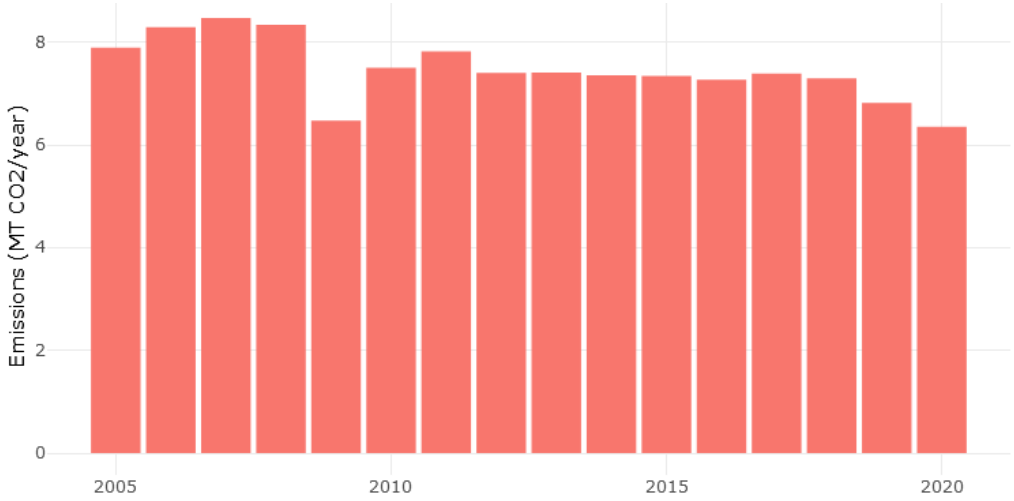


Figure 14 Emissions of lime industry in Germany 2005-2020. Source: Re4Industry, "EEIs Interactive Map" (https://re4industry.eu/eiis-interactive-map/)

The German lime industry will pursue the following decarbonisation measures:

- **Carbon Direct Avoidance (CDA):** Avoidance of CO_2 by using regenerative fuels, hydrogen burners, oxygen burners and electric kilns
- **Smart Carbon Separation (SCS):** CO_2-separation directly inside the kiln or via end of pipe separation with subsequent utilisation (CCU) or storage (CCS)
- **Smart Carbon Capture (SCC):** Natural recovery of CO_2 during the life cycle of lime (NCR) or enhanced carbon capture (ECR) → CO_2 sink

Several projects have already been implemented in Germany in order to innovate the lime sector[30].

Examples include the BiOxySorb project (2013-2016), addressing process emissions mitigation via biomass co-combustion under both air- and oxy-fuel conditions[31]. Under the coordination of the Institute of Combustion and Power Plant Technology (IFK) of the University of Stuttgart, the project partners, including the utility E.ON, the lime technology manufacturer LHOIST and the

(https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

[29] German Lime Association, February 2021, „Lime Industry Roadmap 2050: Climate positive industry through climate neutral production" (https://www.schaeferkalk.de/fileadmin/schaeferkalk/downloads/news/German_Lime_Industry_Roadmap2050_EN.pdf)

[30] European Lime Association (EuLA), 2018, "Innovation in the lime sector 2.0" (https://www.eula.eu/2018-eula-innovation-report/#)

[31] BiOxySorb project: http://bioxysorb.eu-projects.de/

supplies manufacturer GBS, use the data generated in the experimental small, technical and large scale tests to assess the impact of the co-combustion on full-cycle, full-scale power plants and to determine their impact on cycle optimization, ash valorisation and emissions control.

The project ECO – Ecological CO_2 Scrubbing (2010-2012)[32], also contributed to process emissions mitigation. The aim of this research project, led by BV Kalk, was in fact to investigate the recycling of anthropogenic CO_2 into the natural carbon cycle using lime products.

The project ecoloop – Ecological Looping[33] addressed instead improvements in the energy efficiency of lime production. The objective of the project was to assess the generation of gas from synthetic waste (syngas) as an energy surplus. This project, apart from the reduction of energy costs and dependency, also provided environmental benefits such as reduction of residual waste thanks to waste to energy transformation. The technology was tested in one of the plants of the German company Fels, supplier of lime.

[32] ECO project results: https://fg-kalk-moertel.de/forschungsberichte.html
[33] Ecoloop project: https://www.zkg.de/en/artikel/zkg_2012-02_Ecoloop_produces_gas_from_waste_materials_1368451.html

5 Chemicals and Fertilizers

With around 10 percent of total manufacturing industry revenue in 2019, the chemical industry is the third-largest industrial sector in Germany after the automotive, mechanical and engineering sectors.

Germany has the fourth biggest chemical industry in the world in terms of revenues. With yearly revenues of 157 billion euro (2019), it closely follows Japan, which is preceded by China and USA. Therefore, Germany is Europe's chemicals leader and alone it accounts for 27 percent of the EUR 578 billion in sales in the total European market in 2019[34].

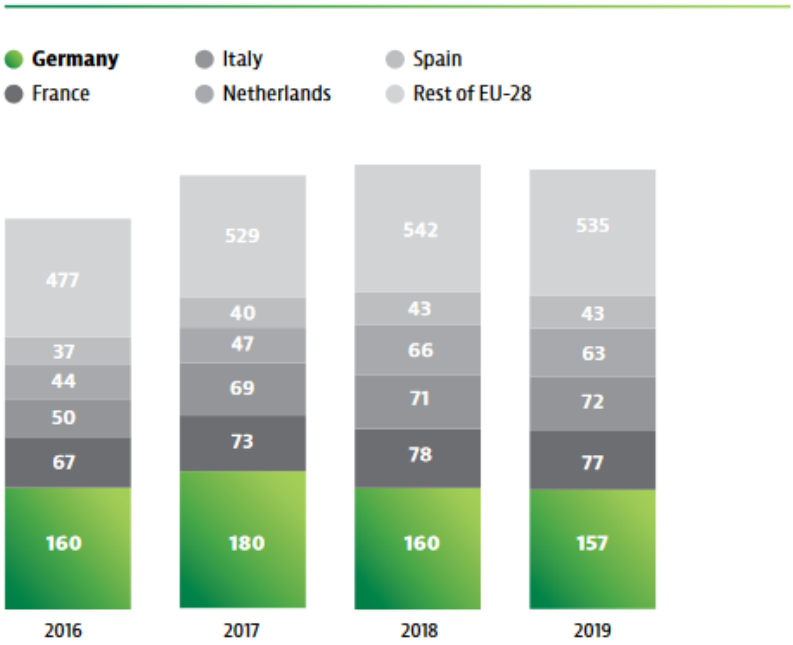


Figure 15 European (EU-28) Chemical Industry Revenue in EUR billion. Source: GTAI – Germany Trade & Invest, 2021, "The Chemical Industry in Germany: Industry Overview" (https://www.gtai.de/resource/blob/64542/9936fdacfc31ec29ebeff9224e2d1141/TheChemicalIndustryGermany.pdf)

During the period 1960 to 2019, chemical and pharmaceutical industry revenue in Germany increased from EUR 12 billion to EUR 198 billion – resulting in an average nominal growth rate of 4.9 percent per year (real growth rate: 3.8 percent per annum). Over the same period, the number of employees has fluctuated but today, at 463,000, it is about the same as it was in 1960 – increasing productivity sixteen fold as indicated by revenue per employee levels of around EUR 428,000 in 2019[35].

[34] GTAI – Germany Trade & Invest, 2021, "The Chemical Industry in Germany: Industry Overview" (https://www.gtai.de/resource/blob/64542/9936fdacfc31ec29ebeff9224e2d1141/TheChemicalIndustryGermany.pdf)
[35] *Ibidem.*

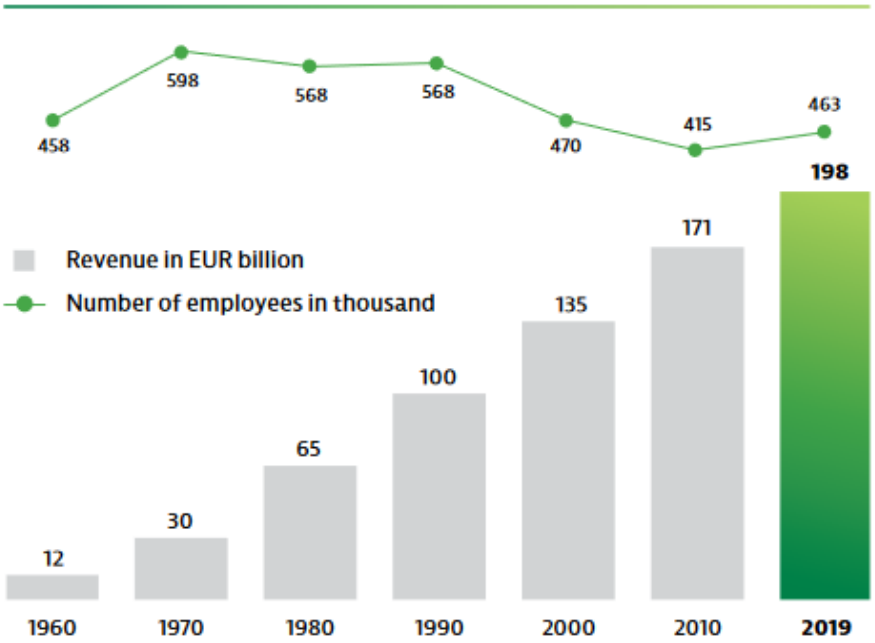


Figure 16 German Chemical Industry Revenue and Employee Development. Source: GTAI – Germany Trade & Invest, 2021, "The Chemical Industry in Germany: Industry Overview" (https://www.gtai.de/resource/blob/64542/9936fdacfc31ec29ebeff9224e2d1141/TheChemicalIndustryGermany.pdf)

There were about 2,900 chemical companies in Germany in 2018, of which 96 percent were small and medium-sized enterprises (SMEs) with less than 500 employees, while the country's top producers account for many globally active chemical companies such as BASF, Bayer, Henkel, Evonik, Covestro, Merck, Lanxess, Freudenberg, Wacker, and Altana[36].

Last but not least, businesses and research institutes involved in the sector invest substantially in research and development activities: R&D spending from German chemical companies (excluding pharmaceuticals) accounted for EUR 4.4 billion in 2019. This makes the industry a driving force for innovation[37].

[36] *Ibidem*.
[37] *Ibidem*.

In the focus: German fertilizers industry

The fertilizer and nitrogen compounds manufacturing industry, as part of the chemical industry, is an essential supplier to the agricultural sector. Germany is an important production location for chemical fertilizers in Western Europe. The market size of the fertiliser and nitrogen compound manufacturing in Germany is of 4 billion euro (not including the manufacture of pesticides, plant protection products and disinfectants), with 11.610 employees and 42 active businesses, including names globally renowned, such as K+S AG, SKW Stickstoffwerke Piesteritz GmbH, Yara GmbH & Co. KG and BASF SE[38].

The fertilizer market is facing major challenges as a result of increasingly stringent regulations and growing environmental awareness, but also because of more efficient agricultural management. The overall trend is to use less and less fertilizer. The fertilizer sector in Germany nevertheless recorded an average annual increase in sales of 3.8% between 2016 and 2021[39] and even the decline of the German grain harvest between 2019 and 2020 and the Corona pandemic did not affect the overall production or supply chains in the mineral fertiliser sector in Germany (see figure below).

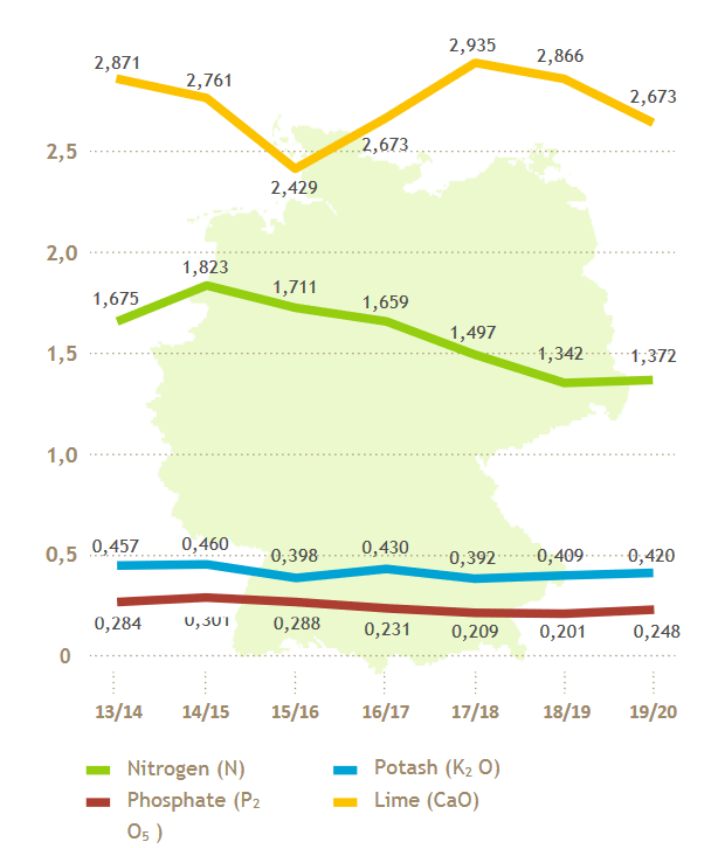


Figure 17 Development of fertiliser sales in Germany in million tonnes. Source: Industrieverband Agrar (IVA), 2021, ""Jahresbericht 2020/2021"

[38] IBISWorld, 2021, "Fertiliser & Nitrogen Compound Manufacturing in Germany - Market Research Report" (https://www.ibisworld.com/germany/industry/fertiliser-nitrogen-compound-manufacturing/747/)
[39] *Ibidem*.

(https://www.iva.de/sites/default/files/benutzer/%25uid/publikationen/iva_jahresbericht_2020_2021.pdf)

GHG emissions and decarbonisation commitments

The emissions from the chemical industry amounted to around 16.9 million tonnes of carbon dioxide equivalents in 2020, which represent a share of 15 percent of the total emissions from all installations subject to EU Emissions Trading System (EU ETS) in Germany. The activity with the highest share of emissions is the production of bulk organic chemicals (46.5%), dominated by the activity of steam cracking, and followed by ammonia production (26.5%). Hydrogen and synthesis gas production and 'Others' fall into the next largest categories at ten and seven percent, respectively. The category 'Others' includes installations of Combustion and Glyoxal and glyoxylic acid production. Other activities have the smallest share at less than five percent each[40].

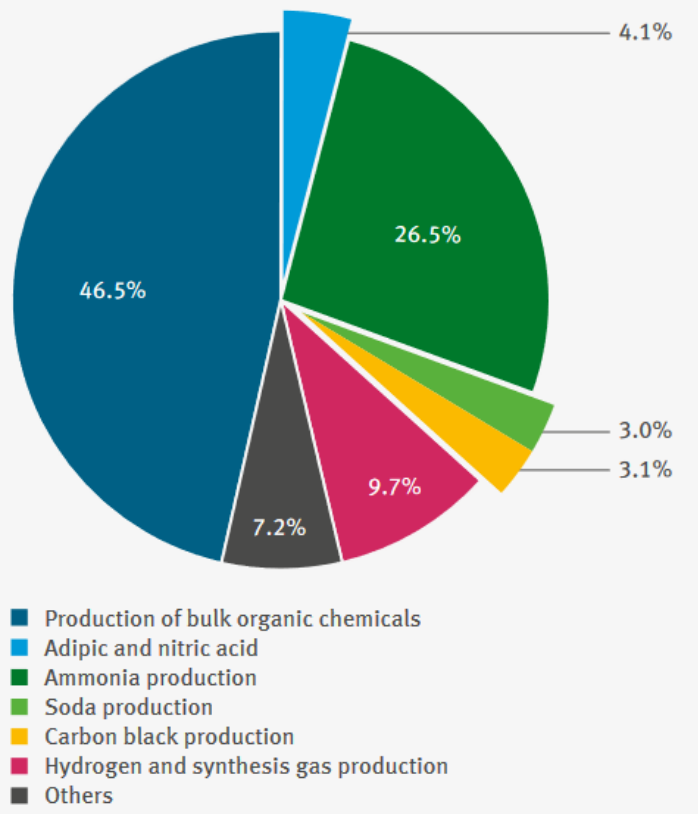


Figure 18 Shares of 2020 emissions from the chemical industry. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)"

[40] Annual emission changes in the industrial sectors since 2013. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

(https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Emissions, activity rates and production indices were within a similar corridor from 2013 to 2019. But looking at the 2013 – 2020 tendency (see figure below), a slow decline in emissions since 2017 can be observed. Part of the decreasing emissions can be explained by a decline in demand from Germany and abroad. At the same time, occasional effects such as the overhaul of crackers (i.e. in 2019, emissions decreased by as much as 372,000 tonnes due to the overhaul of the Böhlen cracker, but before the end of 2020, the cracker had already achieved over 90 percent of its 2018 level[41].

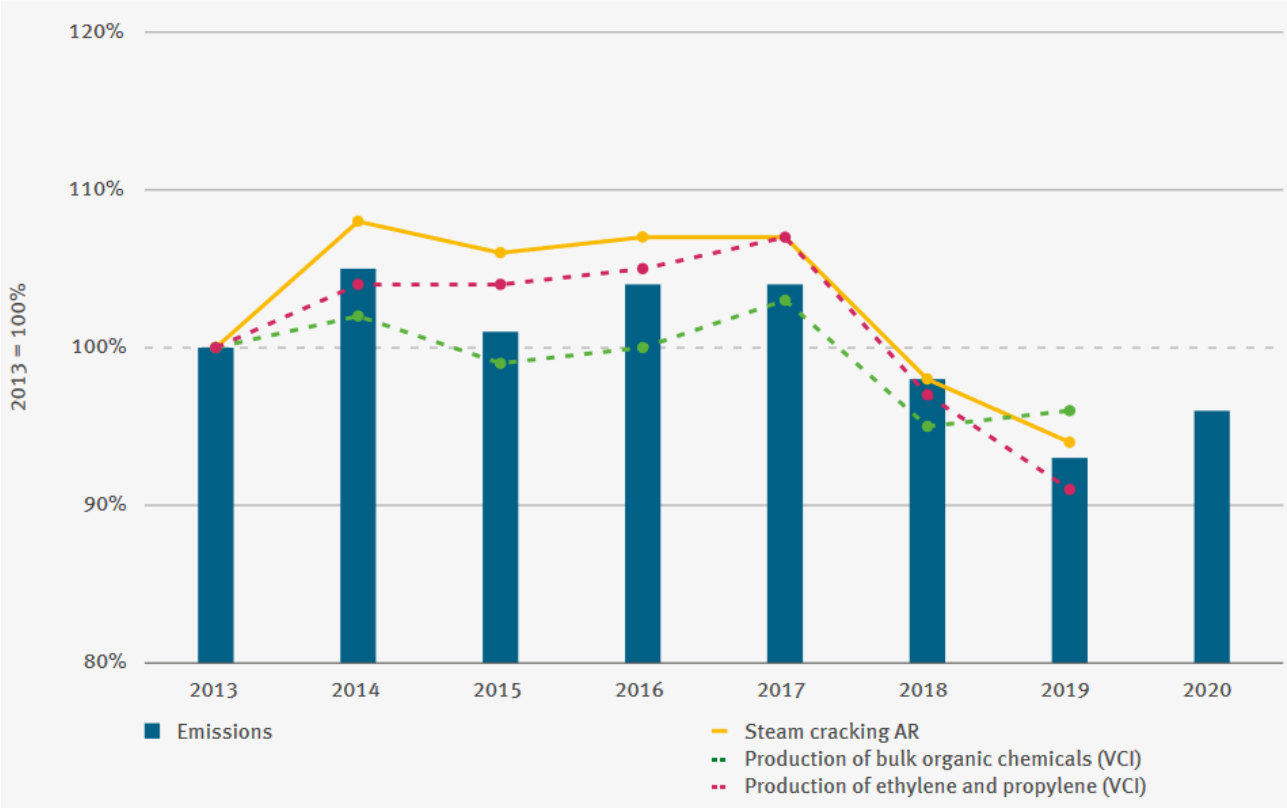


Figure 19 Production of bulk organic chemicals[42], 2013 – 2020 emissions and production trends in Germany, each in relation to 2013. Source: German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)"
(https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Nevertheless, as Germany's third biggest industry, the chemical industry sees itself as being responsible for delivering solutions to contribute to the long-term climate targets.

[41] *Ibidem*.
[42] The figure refers to the 'steam cracking' product benchmark because it makes up a large part of the total EU ETS allocation in the production of bulk organic chemicals activity, with ethylene and propylene being the key products arising from steam cracking.

In 2019 VCI (German Chemical Industry Association) published the study "Working towards a greenhouse gas neutral chemical industry in Germany", which investigates the measures and technologies that the chemical industry needs, how far it can progress towards complete greenhouse gas neutrality and the investments it requires[43].

The study develops three paths to greenhouse gas neutrality that represent different levels of ambition:

- The reference pathway includes efficiency gains via improvements to its current plants, as well as the decommissioning of coal-fired power stations and the continuing development of renewable energies, which lead to a reduction in emissions from the production of electricity purchased by the chemical industry from outside.
- The technology pathway introduces new process technologies in basic chemistry. The industry can thereby greatly reduce energy-related and process emissions previously attributed to chemistry. Greenhouse gas emissions remain from the use of fossil resources as a source of raw materials and for combustion processes. These can also be partially replaced by alternative sources. The industry is making further progress by reusing plastics as a starting material for the production of basic chemicals through improved mechanical and chemical recycling.
- The GHG-neutrality pathway: to achieve extensive greenhouse gas neutrality in the German chemical industry by 2050, the efforts described in the limited technology pathway would have to be ramped up. In this pathway, technologies are implemented if their use results in a saving on CO_2, irrespective of their economic viability. All conventional basic chemical procedures would thus be replaced by alternative processes without CO_2 emissions by 2035 to 2050.

[43] DECHEMA and FutureCamp study for the VCI, 2019, "Working towards a greenhouse gas neutral chemical industry in Germany – Summary" (https://www.vci.de/langfassungen/langfassungen-pdf/vci-study-greenhouse-gas-neutrality-in-the-german-chemical-industry.pdf)

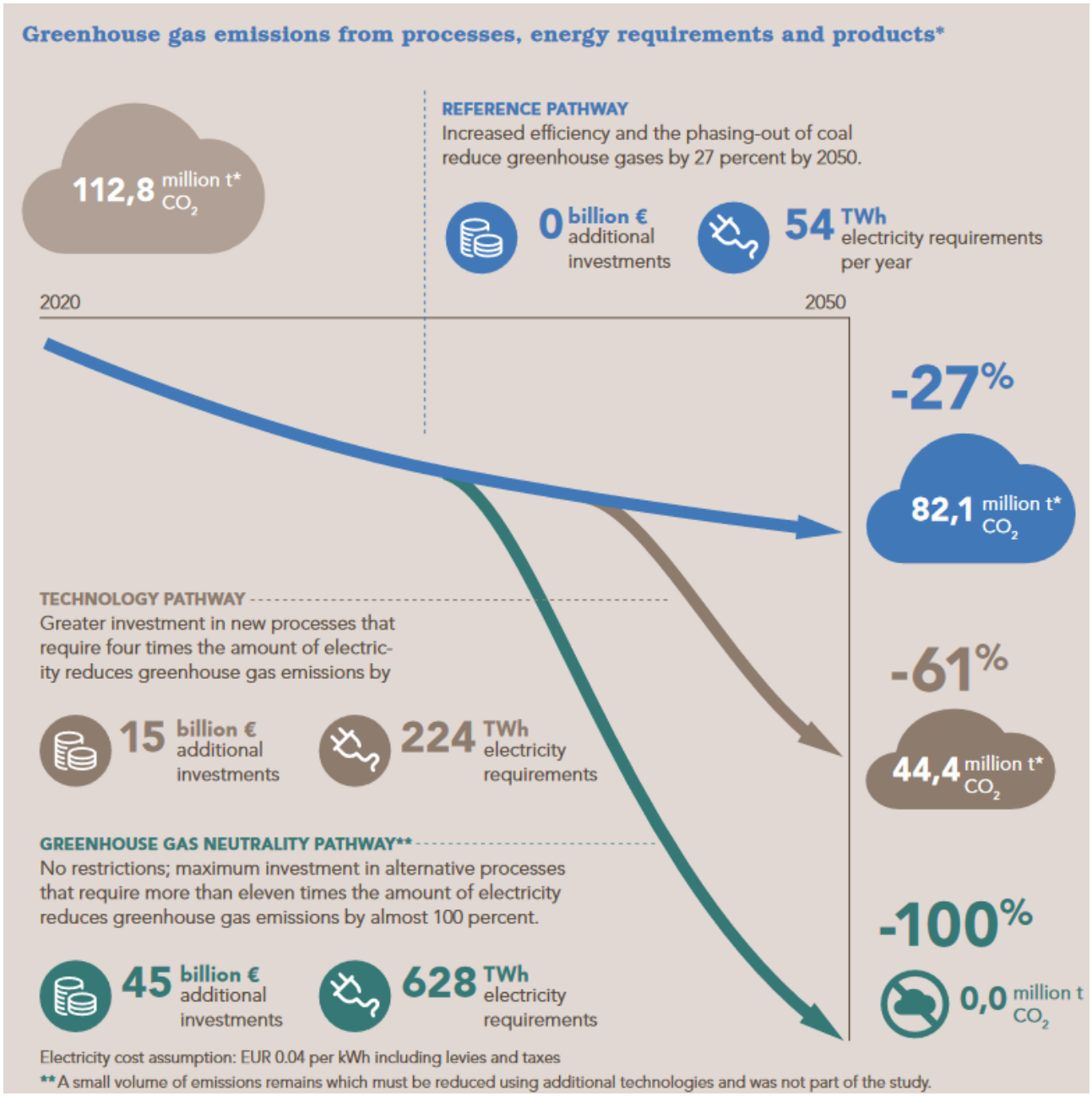


Figure 20 Results of the VCI study "Working towards a greenhouse gas neutral chemical industry in Germany" in brief. Source: DECHEMA and FutureCamp study for the VCI, 2019, "Working towards a greenhouse gas neutral chemical industry in Germany – Summary" (https://www.vci.de/langfassungen/langfassungen-pdf/vci-study-greenhouse-gas-neutrality-in-the-german-chemical-industry.pdf)

The roadmap for the German chemical industry shows that it is technologically feasible for chemical production in Germany to become extensively greenhouse gas-neutral by 2050. New methods of closed-loop circulation, CO_2-free hydrogen production and the use of CO_2 as a raw material make this possible. Nevertheless, the extent to which the chemical industry can actually tap this technical potential depends on multiple factors. In fact, companies can only advance the transformation

towards zero emissions if they remain competitive at every stage and find favourable framework conditions. But even then, there are high hurdles in the way of greenhouse gas neutrality in chemistry: an important prerequisite for almost all new technologies is the availability of renewable electricity in gigantic quantities from today's perspective and at a cost of 4 cents per kilowatt hour. Without these boundary conditions, the introduction of the new technologies to reduce CO_2 is not worthwhile. If electricity is more expensive, the implementation of new processes will be delayed until well after 2050[44].

[44] *Ibidem*.



6 Steel

Germany is the biggest steel manufacturer in the EU and among the top 10 worldwide. Germany accounts for around a quarter of EU steel production (35.7 million tons produced in 2020) – ranking first ahead of Italy (20.4 million tons) and France (11.6 million tons).

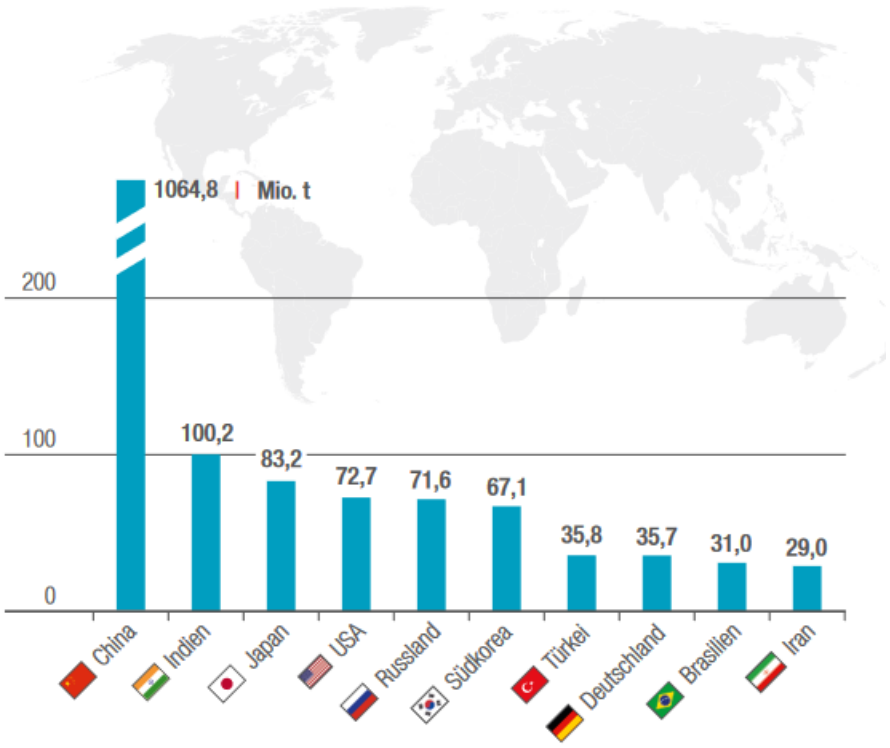


Figure 21 The top 10 crude steel producers in the world (2020). Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

Steel factories are scattered across the country, with a major concentration in the West[45].

[45] Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

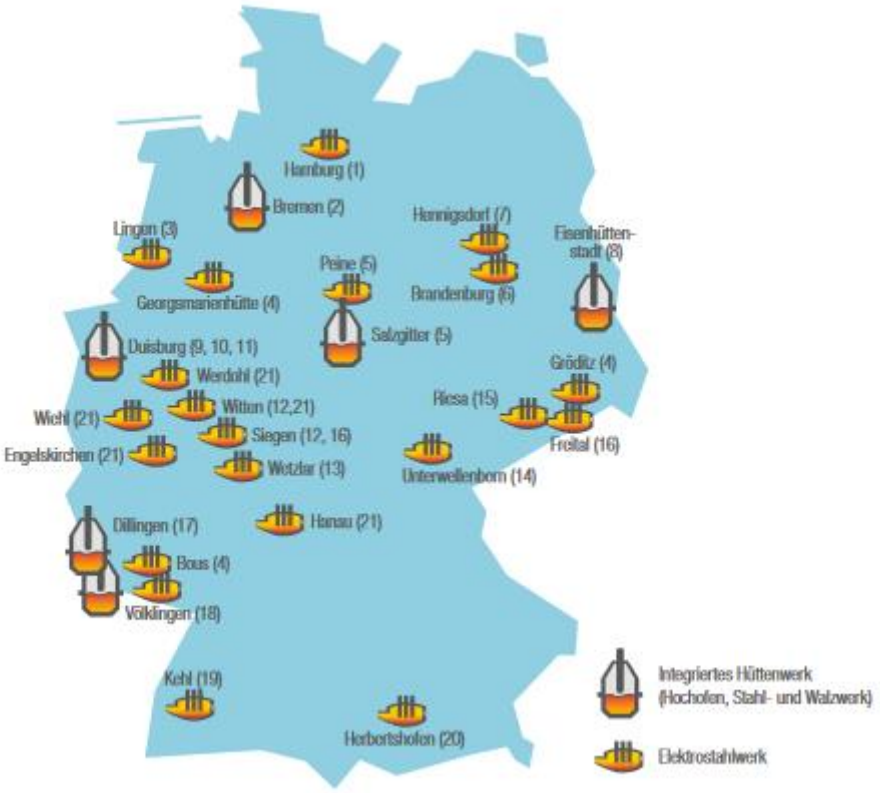


Figure 22 Steel production sites in Germany. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

In 2020 Germany produced 35.7 million tons of crude steel[46]. The decrease in production from the previous year was due to the negative effects of the COVID-19 pandemic on the entire economy, including on important steel-using industries. Nevertheless, production and sales were able to recover in 2021 compared to the severe contractions of the previous year, and crude steel production in Germany exceeded the 40 million tons mark again[47].

[46] *Ibidem*.
[47] Wirtschaftsvereinigung Stahl, 2022, „Informationen zur Stahlkonjunktur in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/2022-01_Stahlkonjunktur_Deutschland_WVStahl.pdf).

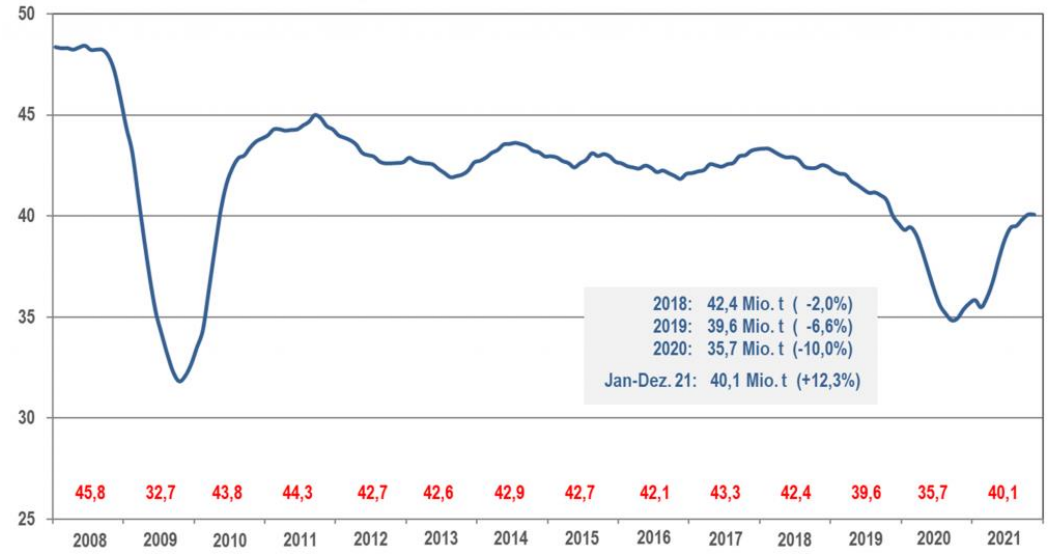


Figure 23 Crude steel production in Germany. Source: Wirtschaftsvereinigung Stahl, 2022, „Informationen zur Stahlkonjunktur in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/2022-01_Stahlkonjunktur_Deutschland_WVStahl.pdf).

The decrease in production was clearly reflected also in the sales revenues of German steel companies, which in 2020 were lower than in 2009 (during the financial and economic crisis)[48].

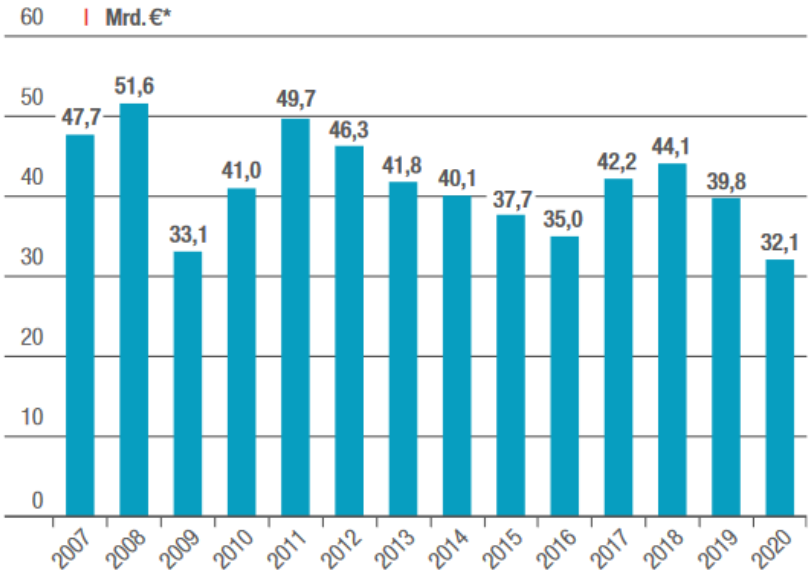


Figure 24 Revenues of steel companies in Germany 2007-2020. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

[48] Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

This decrease is no surprise since the majority of Germany's manufacturing sector is steel-intensive. The request for steel mainly comes from the construction sector (35%), the automotive industry (26%) and the mechanical engineering sector (11%)[49].

German steel companies are highly competitive and technological leaders in the sector. In fact, new and innovative equipment allowed to double the productivity of the German steel industry since the country's reunification at the beginning of the 1990s, even though in the same period the number of employees fell from 179.000 to 83.000[50].

Taking into account also the largest steel-intensive industrial sectors, the number of employees today amounts to about 4 million, corresponding to around two thirds of jobs in the whole German industrial sector[51].

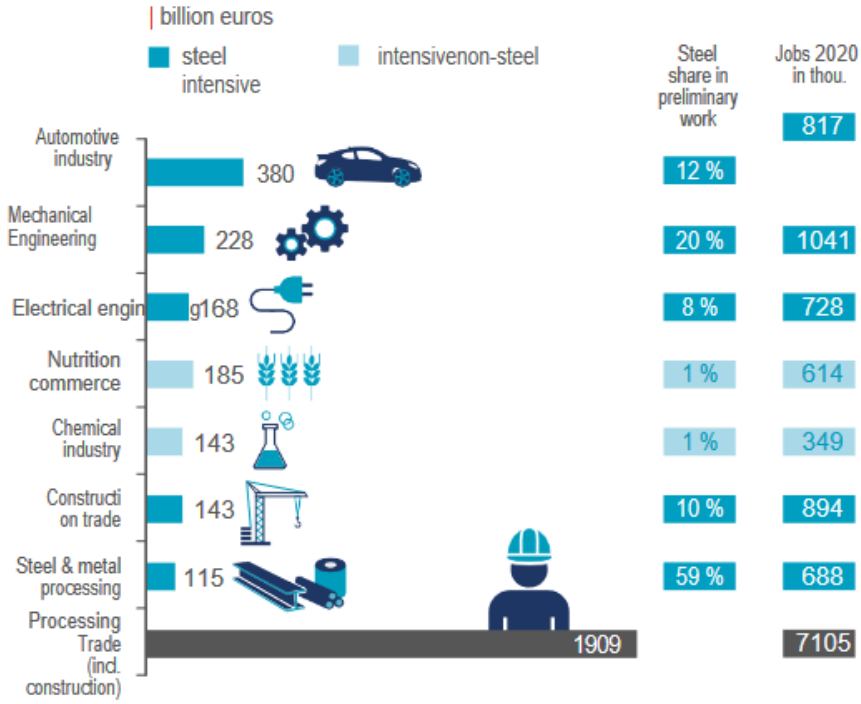


Figure 25 Steel-intensive sectors in Germany and number of employees per sector. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland" (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

GHG emissions

The steel industry accounts for around 30 percent of industrial emissions in Germany, having emitted 52.6 million tons of CO_2 equivalent in 2019[52].

[49] *Ibidem*.
[50] *Ibidem*.
[51] *Ibidem*.
[52] *Ibidem*.

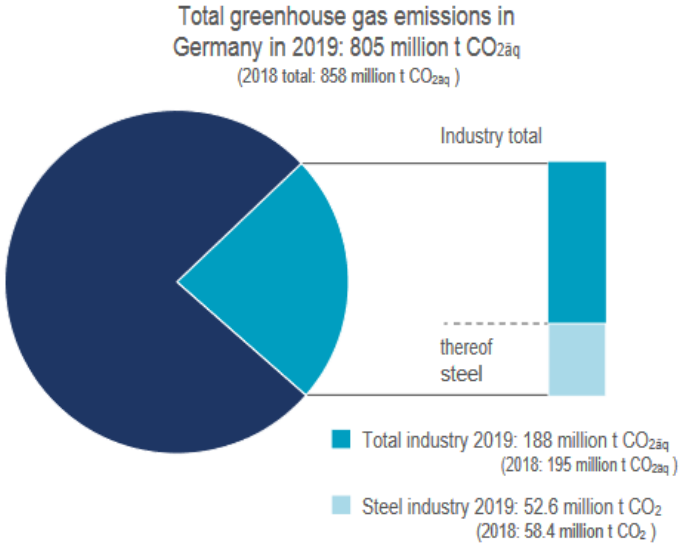


Figure 26 Greenhouse gas emissions in Germany in 2019 (total industry and steel industry). Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

Steel production installations using the blast furnace route (oxygen steel) dominate the emissions of the iron and steel industry with a share of almost 84 percent, even though they account only for about 68 percent of crude steel production. In contrast, emissions from electric steel production, which accounts for 30 percent of total crude steel production in Germany, are comparatively low at about three percent. Emissions from iron and steel processing account for about 13 percent[53].

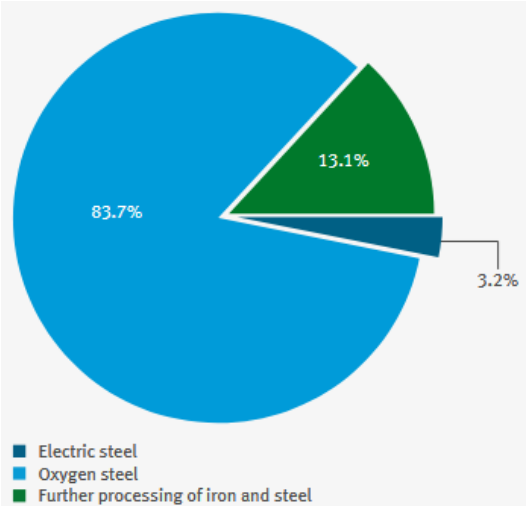


Figure 27 2020 emissions distribution in the iron and steel industry. Source: German Emissions Trading

[53] German Emissions Trading Authority (DEHSt), 2021, “Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)” (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3)

Today, compared to 20 years ago, around one fifth less of CO_2 is emitted per tonne of steel produced. However, the established steel production methods have now reached their decarbonisation limits. In order to further reduce CO_2 emissions from steel production, companies in Germany must work intensively on the introduction of alternative low-CO_2 production processes. Such a radical transformation in the way steel is produced poses considerable economic challenges for the steel industry and is therefore closely linked to fundamental changes in the political framework conditions.

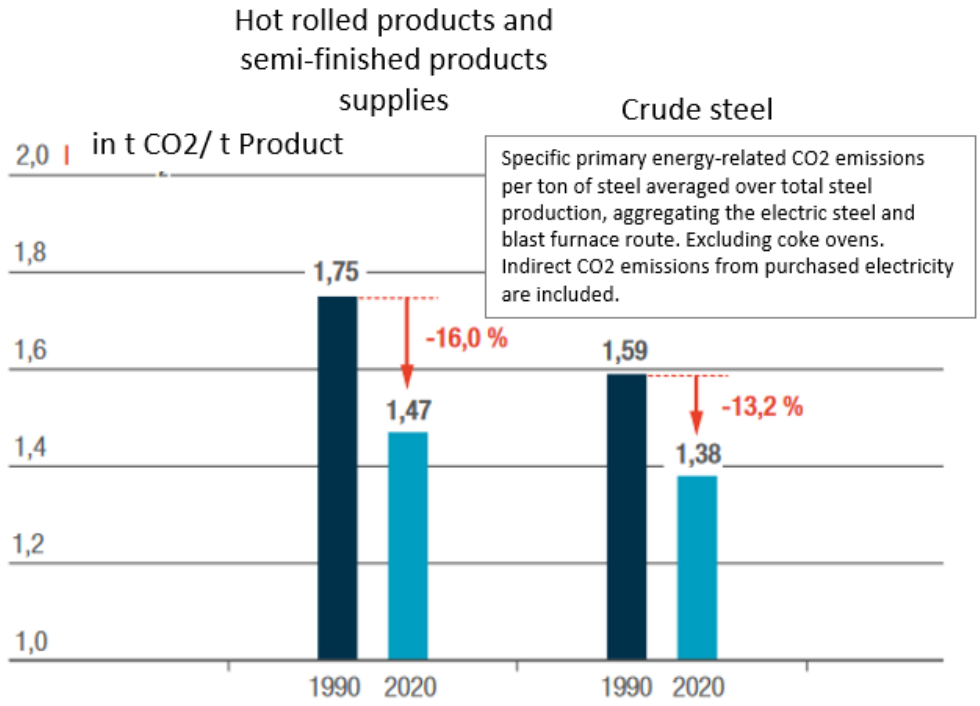


Figure 28 Development of specific energy-related CO_2 emissions in the German steel industry. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland" (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

Decarbonisation potential

The steel industry in Germany is already producing steel under the best conditions in the world, in terms of environmental impact, but further massive efforts are still required and an enormous leverage effect can be achieved with the rapid conversion of steel production processes to climate-friendly hydrogen-based technologies. This effect would be reinforced by the position of the steel industry at the beginning of international value chains, which makes GHG-neutral steel production key in order to achieve the European climate goals and to meet the obligations of the Paris agreement.

The use of just one ton of hydrogen in the steel industry can save up to 28 tons of CO_2 compared to traditional production processes. Hydrogen use has the greatest CO_2 reduction potential in the steel industry compared to other sectors of the economy (i.e. the CO_2 reduction potential of hydrogen use

in the transport sector is only of 5 to 17 tonnes, as shown in the figure below)[54].

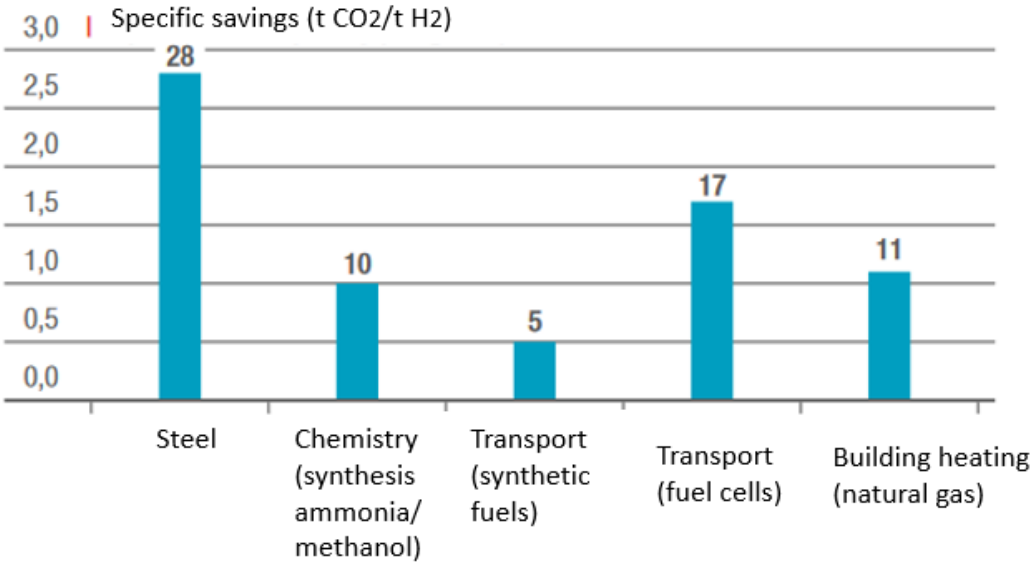


Figure 29 Hydrogen use: CO_2 reduction potential in sectors comparison. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland" (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

Thanks to hydrogen the steel industry could be almost entirely decarbonized and up to 95 percent of the emissions in the most CO_2-intensive industrial sector could be saved. Nevertheless, this achievement would require more than two million tons of hydrogen per year, which would allow to save over 50 million tons of CO_2 per year (equivalent to the total emissions of Portugal)[55].

The greatest CO_2 savings potential lies in the blast furnace route, where the highly intensive CO_2 process could be carried out with hydrogen in the future. Further areas of application for hydrogen in the steel industry are in the replacement of natural gas in electric steel production (which has already low CO_2 emissions compared to the blast furnace route), and in steel processing.

For this hydrogen conversion to be successful, the production of the hydrogen used by the steel industry should obviously be clean (i.e. green, blue or turquoise hydrogen). However, low-carbon hydrogen is today virtually unavailable and more expensive than conventional grey hydrogen, which pollutes the environment during its production, even though Germany is working on its "National Hydrogen Strategy[56]".

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[54] Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland" (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

[55] Wirtschaftsvereinigung Stahl, 2021, "Engagement für Stahl – Jahresbericht 2021" (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Jahresbericht_2021_RZ_Web-1.pdf#%5B%7B%22num%22%3A149%2C%22gen%22%3A0%7D%2C%7B%22name%22%3A%22Fit%22%7D%5D)

[56] Federal Ministry for Economic Affairs and Climate Action, 2020, "The National Hydrogen Strategy" (https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-

Economic viability poses the greatest challenge for the German steel industry, especially because the steel industry faces tough international competition. To achieve a climate-neutral steel industry, steel companies in Germany need in fact fair international competitive conditions. These include, in particular, effective protection against the migration of energy-intensive industrial production to other regions of the world with lower climate protection standards. If this so-called “carbon leakage” is not prevented, serious negative impacts on the climate, economy and employment will result[57].

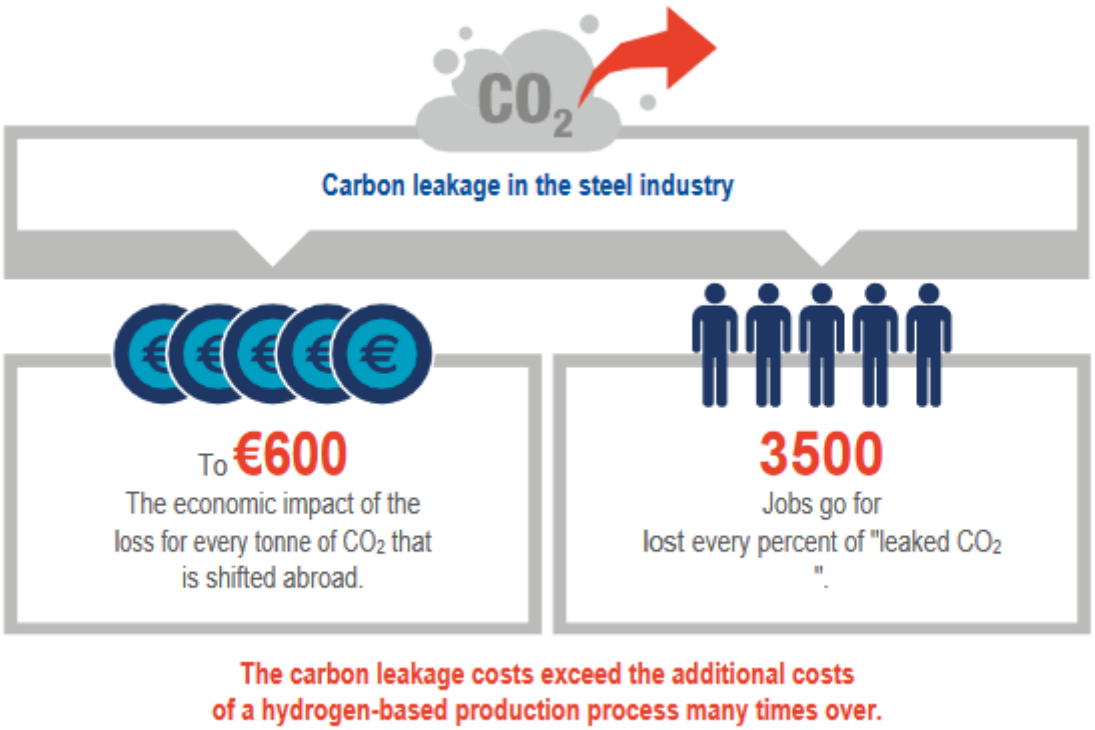


Figure 30 Macroeconomic consequences of carbon leakage in the steel industry. Source: Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

Suitable regulatory and policy framework conditions from German and European policy-makers are therefore indispensable both for the success of the hydrogen-based transformation of the steel industry and for the ramp-up of the hydrogen economy as a whole. In concrete terms, this means that until the scarcity of clean hydrogen is overcome, the regulatory framework should ensure the prioritization of hydrogen use in those sectors where it has the greatest potential for avoiding CO_2 emissions (i.e. steel production).

Additional potential for the decarbonisation of the steel industry lies in the circular economy and the recycling of steel. Steel is 100 per cent recyclable without any loss of quality. The steel industry in

strategy.pdf?__blob=publicationFile&v=6).

[57] J. Limbers, Dr. M. Böhmer, 2022, “Transformation Paths for the Steel Industry in Germany - Non-technical version of the study” (https://www.stahl-online.de/wp-content/uploads/202203_WVS_Transformationpaths_Steel_Germany_Prognos_ENG.pdf)

Germany alone uses around 20 million tonnes of scrap steel and iron every year to make new products. A well-functioning steel recycling system is already established in Germany and because there is no loss of quality, steel can be recycled again and again (i.e. one tonne of steel can be recycled six times to produce a total of four tonnes of new steel products)[58].

[58] Wirtschaftsvereinigung Stahl, 2021, „Fakten zur Stahlindustrie in Deutschland“ (https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2021_RZ_Web_neu.pdf).

7 Glass

The German glass industry relies on the production of almost 400 factories with a minimum of 20 employees (388 factories in 2020), which produced 7.356 tons of glass in 2020. In the same year, the total number of employees in the glass industry was ca. 54.000[59]. The factories are spread across the whole country, and most of them are members of the Federal Association of the German Glass Industry (BV Glas), as shown in the map below.

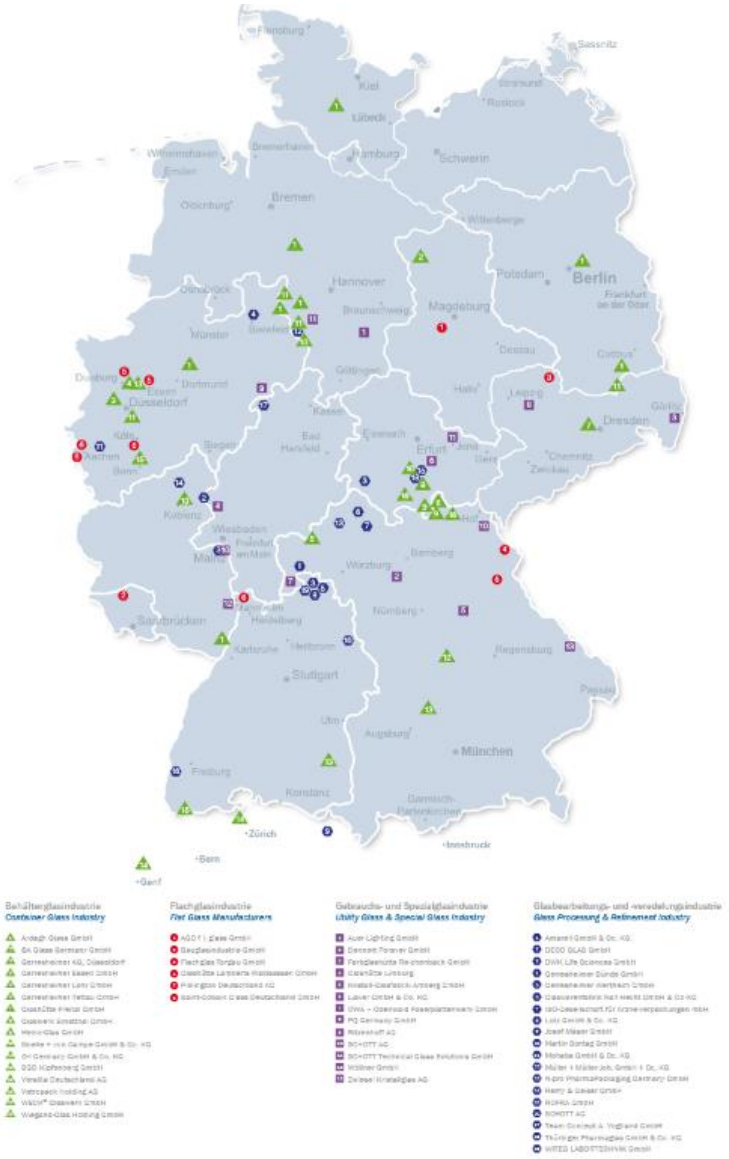


Figure 31 Members of the Federal Association of the German Glass Industry. Source: BV Glas, 2020, "Annual Report 2019" (https://www.bvglas.de/media/BV_Glas/Jahresbericht_2019.pdf)

[59] BV Glas, 2021, "The German glass industry at a glance in 2019 and 2020" (https://www.bvglas.de/media/Facts_and_figures_Jahresberichte/Ueberblick_Glasindustrie.pdf)

Total glass industry revenues in Germany are declining year-by-year and in 2020 they amounted to around EUR 9.35 billion (while in 2019 they amounted to EUR 9.8 billion and in 2018 to EUR 10.05 billion). Both domestic and foreign revenues are shrinking (in 2020 they shrank by 4.0 and 5.5 percent respectively, compared to 2019)[60].

The German glass industry is composed of many different sectors, with the most important ones in terms of revenues being the flat glass finishing sector and the container glass sector.

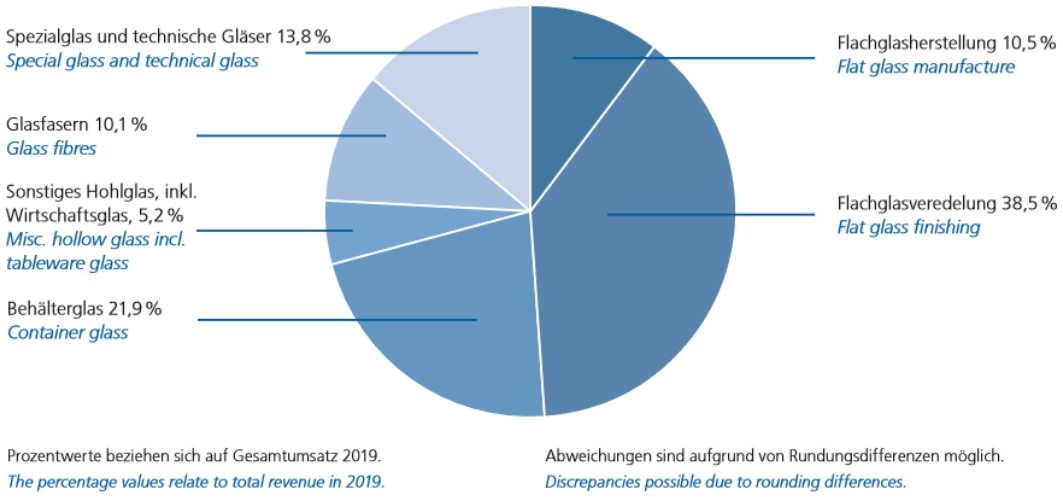


Figure 32 Glass industry revenue by sector. Source: BV Glas, 2020, "Annual Report 2019" (https://www.bvglas.de/media/BV_Glas/Jahresbericht_2019.pdf)

These sectors serve different industry customers, such as the construction industry, the food and beverage industry and the chemicals, pharmaceuticals and cosmetics industry.

[60] *Ibidem*.

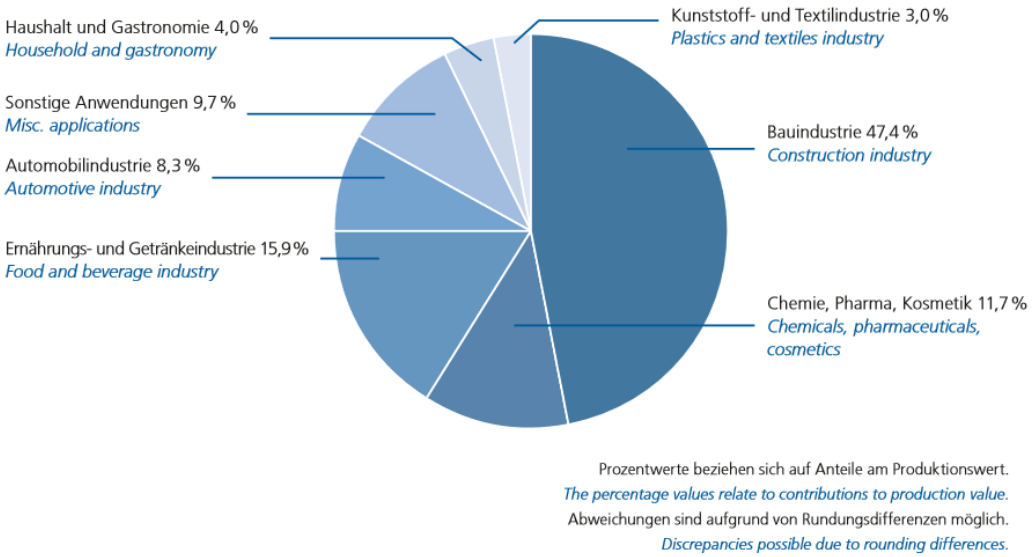


Figure 33 Glass industry customers. Source: BV Glas, 2020, "Annual Report 2019" (https://www.bvglas.de/media/BV_Glas/Jahresbericht_2019.pdf)

GHG emissions and decarbonisation commitments

The glass industry is one of the most energy intensive industries in Germany. It is estimated that emissions from the installations for glass production amounted to around 3.9 million tonnes of carbon dioxide in 2020[61]. Most of the energy requirement occurs during the melting process, which is mainly covered by the combustion of fossil fuels (natural gas and occasionally heating oil) and the direct supply of energy through electricity[62].

As an energy-intensive industry, the glass industry is subject to energy and climate policy regulations, which affect its production operations and competitiveness. Since 1970, the German glass industry has reduced its energy consumption levels by 77 percent, which is close to the maximum energy efficiency that is technically feasible in glass production, and most companies have more or less already maximised their energy efficiency[63].

The potential for making the glass manufacturing process more flexible is severely limited by two factors. On the one hand, due to the melting process, glass production is a continuous process that is operated 8,760 hours a year. On the other hand, the liquid glass must adhere to a strict temperature-time profile after and during the melting process in order to have the viscosity required for the process[64].

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[61] German Emissions Trading Authority (DEHSt), 2021, "Greenhouse Gas Emissions in 2020 Stationary installations and aviation subject to emissions trading in Germany (2020 VET report)" (https://www.dehst.de/SharedDocs/downloads/EN/publications/2020_VET-Report.pdf;jsessionid=E99E57244BF0415C3D836FD652A7D02A.2_cid321?__blob=publicationFile&v=3).
[62] Leisin M., 2020, „Energiewende in der Industrie Potenziale und Wechselwirkungen mit dem Energiesektor Flexibilitätssteckbrief der Glasindustrie" (https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2b-flexibilitaetssteckbrief-glas.pdf?__blob=publicationFile&v=6).
[63] BV Glas, "Energy and climate" (https://www.bvglas.de/en/business-segments/energy-and-climate/).
[64] Leisin M., 2020, „Energiewende in der Industrie Potenziale und Wechselwirkungen mit dem Energiesektor Flexibilitätssteckbrief der Glasindustrie" (https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-

At the same time, the European Emissions Trading System is putting significant strains on the German glass industry. In fact, while energy suppliers can pass on the costs for emissions trading certificates to their customers, the glass industry cannot. Without the allocation of free certificates, the European glass industry would be severely disadvantaged over global competitors. The total volume of available certificates will fall after 2021 at increased speed, by 2.2%. In particular, the indirect costs that must be borne by the glass industry following the rise in electricity prices, brought about by the ETS, will increase sharply in the upcoming trading period.

Therefore, the glass industry will only be able to continue manufacturing in Germany in the long term if the regulatory framework allows to fairly plan ahead. After all, the German glass industry, with its diverse products ranging from heat-insulating windows to resource-saving container glass, reinforcing glass fibres in wind turbines and special glass for the semiconductor industry, is an essential sector for the energy transition.

In order to make the manufacturing of glass products climate-neutral in the future, German glass manufacturers must make an enormous effort, which is impossible without the appropriate framework conditions and the preservation of competitiveness. The glass industry is making a significant contribution to the development and industrialisation of climate-neutral hydrogen-based technology[65]. Within the glass melting process, green electricity and hydrogen are key for the industry to achieve climate neutrality. Green hydrogen should therefore be made available in sufficient quantities for the glass industry in the near future and at competitive prices[66].

der-industrie-ap2b-flexibilitaetssteckbrief-glas.pdf?__blob=publicationFile&v=6).

[65] Together with the Gas- und Wärme-Institut Essen e.V., BV Glas is investigating the possibility of using hydrogen in the glass industry (more information on the HyGlass project at this link: https://www.bvglas.de/dekarbonisierung/hyglass-wasserstoffeinsatz-in-der-glasindustrie/).

[66] BV Glas, 2021, " BV Glas-Stellungnahme zu dem Entwurf der EU Klima-, Umwelt- und Energiebeihilfeleitlinien 2022" (https://www.bvglas.de/index.php?eID=dumpFile&t=f&f=2333&token=8abc05fe00e3eac33279f1763eef9ef8d26d831c).



In the focus: re-use and recycling in the German glass industry

Reusable packaging is part of the packaging culture in Germany – more so than in any other European country – especially in the beverages segment.

Reusable glass bottles are especially popular in the beer and water segments for good reason: they can be reused up to 50 times, thus contributing to waste prevention. Reusable glass bottles also have a positive environmental impact: in the first 10 trips, the environmental impact is reduced by 90 percent[67]. It makes most sense to fill reusable glass bottles for products that will be consumed relatively quickly in order to make full use of the recycling process advantages. Reuse systems, such as those in the beer and water segments, have existed for decades. They depend on the bottles being returned to circulation quickly so that there are always enough bottles in stock for the re-filling process.

Regionality is another important aspect, because the shorter the transportation routes, the lower the environmental impact of reusable bottles. In other segments such as wine (which has an import rate of ca. 50% in Germany) or preserved food, single-use glass packaging makes more sense. The establishment of an intercontinental reuse system would in fact not be convenient from an ecological viewpoint and single-use glass is therefore to be recycled.

The new German Packaging Act states that by 2022, 90 percent of the single-use glass packaging on the market in Germany will have to be collected and recycled. BV Glas has been promoting the quality of recycled glass through its involvement in the recycling campaign “Nicht alles passt ins Altglas” (“You can’t put everything in the bottle bank”) since 2011, and it supports the European “Close the Glass Loop” initiative, which aims to increase the glass recycling rate in Europe.

[67] BV Glas, 2020, “Annual Report 2019” (https://www.bvglas.de/media/BV_Glas/Jahresbericht_2019.pdf).



8 Ceramics

Germany is home to 314 ceramics production facilities, belonging to 227 companies, distributed throughout the whole country with a total production volume of 11.2 million tons (figures from 2016)[68]. These companies can vary a lot in size, ranging from large companies with high production volumes and subject to the EU ETS, to small specialised companies with a limited number of employees. In total, the German ceramics industry employed 33.452 people in 2016[69].



Figure 34 Selected locations of the ceramic industry. Source: Hübner T., Guminski A., von Roon S., 2020, „Energiewende in der Industrie – Potenziale und Wechselwirkungen mit dem Energiesektor: Branchensteckbrief der Keramikindustrie“ (https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2a-branchensteckbrief-keramik.pdf?__blob=publicationFile&v=4).

Germany is the second largest producer of ceramics in Europe, after Italy. The ceramics industry in Germany achieved a turnover of approximately 5.5 billion euro in 2016, unevenly distributed between six different ceramics sectors: household ceramics, sanitary ware, technical ceramics, wall and floor tiles, bricks and refractory ceramics. Depending on the economic sector, the export share is between 25 and 60 percent of German production[70].

[68] Hübner T., Guminski A., von Roon S., 2020, „Energiewende in der Industrie – Potenziale und Wechselwirkungen mit dem Energiesektor: Branchensteckbrief der Keramikindustrie“ (https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2a-branchensteckbrief-keramik.pdf?__blob=publicationFile&v=4).
[69] *Ibidem*.
[70] *Ibidem*.

In terms of energy consumption, the German ceramics industry consumed 11.4 TWh of energy in 2016, predominantly in the form of thermal energy (10 TWh), while the remaining energy is consumed in the form of electricity (1.4 TWh). The use of thermal energy is the highest in the tile and brick industries (about 90 percent, and the remaining 10 percent is electricity). In the crockery and refractory industry, as well as in the production of sanitary ceramics, the electricity share is somewhat higher at 15 percent, and significantly higher in technical ceramics at around 25 percent. In the entire ceramics industry, natural gas is the main fossil fuel used (approx. 95 percent). Depending on the product, however, the specific energy consumption varies considerably, while independently on the product, the firing is always the most energy-intensive step in the manufacturing process of ceramics, consuming on average 80-90 percent of the total energy consumption in the whole process[71].

GHG emissions and decarbonisation commitments

As an energy-intensive industry, emitting 3.36 million tons of CO_2 equivalent per year (2016 figure)[72], the German ceramics industry is particularly committed towards the energy transition, notwithstanding the intense international competition from foreign manufacturers.

In the ceramics industry, an important step towards the reduction of CO_2 emissions has already been achieved with the replacement of solid fuels by gases in ceramic burners. Biomass and synthetic fuels offer the possibility of further achievements in the reduction of GHG emissions. CCU could prove very helpful here, because it offers the advantage of being able to produce synthetic fuels for the fuel-based processes in the ceramics industry from the captured CO_2. However, the exhaust gas flow in the ceramics industry is currently too low in CO_2 for efficient CO_2 separation and capture. An additional downside comes from the fact that feeding methane from regenerative sources (biomass or power-to-methane) into the existing natural gas network can have a negative impact on ceramics product quality and on the service life of the furnaces.

Alternative options which could significantly reduce CO_2 emissions include partial electrification of the burner, but electric heating has yet to be developed for large, continuously operated tunnel kilns. Not only technologies such as electric industrial furnaces in the required dimensions will not be available in the foreseeable future, but also their operation would not be economically viable in view of the high electricity prices.

An additional way to reduce energy consumption, and consequently energy costs, would be to use flexibility in the process. This would be a particularly advantageous solution for the ceramics industry, since energy costs make up around 30 percent of all production costs, since the firing process requires continuously operated kilns, which depend on a continuous, uninterrupted power supply.

As an energy-intensive sector, the German ceramics industry is also particularly dependent on competitive and stable energy prices. Due to the high proportion and the unavoidable process-related emissions in ceramic production without CCS, future production costs are also largely dependent on the design of EU emissions trading. In the framework of the EU ETS, carbon leakage protection towards countries with lower environmental standards (especially when it comes to high-temperature processes for the manufacture of refractory and technical ceramics) is required to

[71] *Ibidem*.
[72] *Ibidem*.

ensure reliable framework conditions for future investments and to take international competitive pressure into account.



9 German EEIs decarbonisation challenges and potential measures

Germany is one of the world's leading industrial locations. More than seven million employees in the manufacturing sector generate a fifth of the national value added. With the energy transition, Germany is pursuing an ambitious energy and climate policy. As part of the Paris climate agreement, Germany committed itself to taking steps to limit global warming to 1.5°C, and national commitments pledge an emissions reduction by 65 percent compared to 1990 levels by 2030 and climate neutrality by 2045.

With the industrial sector being responsible for a fifth of Germany's greenhouse gas emissions (and with EEIs generating the biggest share of these emissions), the decarbonisation of the sector is key to achieve long-term goal of greenhouse gas neutrality. In recent decades, German industry has already made great progress in reducing greenhouse gas emissions and reduced its greenhouse gas emissions by a third between 1990 and 2018, without losing its strong position on the world market. More than that, the industrial sector has committed to reducing emissions by around 56 million tonnes (around 29 per cent) by 2030 (compared to 2018levels)[73].

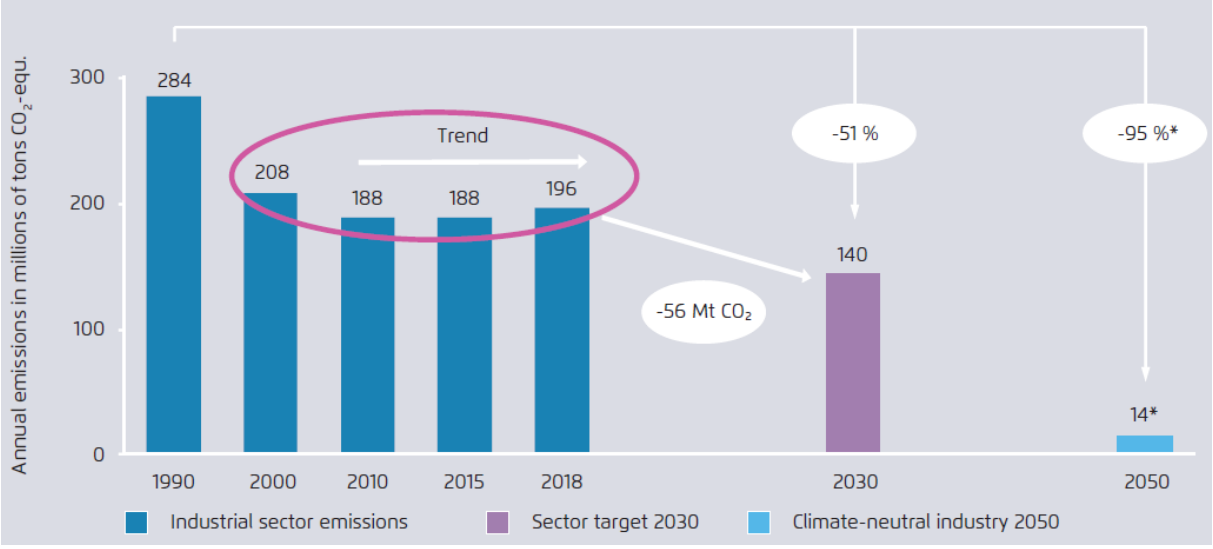


Figure 35 Emissions of the German industrial sector 1990-2018 and sector targets 2030/2050. Source: Agora Energiewende and Wuppertal Institute, 2019, "Climate-Neutral Industry (Executive Summary): Key Technologies and Policy Options for Steel, Chemicals and Cement"

Nevertheless, further – and enormous – efforts still have to be made in order to achieve these objectives, and the previous chapters made clear that they cannot be achieved solely through further

[73] Agora Energiewende and Wuppertal Institute, 2019, "Climate-Neutral Industry (Executive Summary): Key Technologies and Policy Options for Steel, Chemicals and Cement".

increases in energy efficiency: over the last ten years, the industrial sector has increased its efficiency, but without achieving a corresponding reduction in emissions. Rather, fundamental changes in production processes will be necessary.

But there are two big impediments to these fundamental changes.
First, about one-third of emissions from EEIs take the form of process-related emissions, which cannot be avoided using conventional production techniques due to the raw materials used and to the associated chemical reactions.
A study[74] carried out in the framework of the Federal Ministry for Economic Affairs and Climate Action (BMWK)'s project "Energy transition in industry: potential, costs and interactions with the energy sector[75]", demonstrates that the transformation of industry is technically possible, even though the challenges are great, because industrial production processes that have been tested and applied over decades have to be fundamentally changed, and because almost all of the emission-avoiding technologies are associated with high additional costs.

The BMWK's project divides the possible approaches into three groups:

1. Electrification: this is mainly about making processes for heat generation in EEIs run fully on green electricity. In fact, if the power supply is increasingly generated by renewable energy sources and greenhouse gas-neutral, emissions will be saved on a large scale.
2. The use of bio or synthetic fuels: this primarily consists of replacing fossil fuels, for example with biomass or greenhouse gas-neutral synthetic gases. But it should be noted that even if the use of biomass or bioenergy is generally a comparatively inexpensive and very effective option, the availability of biomass is limited, and it is also seen as a solution in other areas (residential heating, shipping and air traffic) to achieve climate neutrality. This raises the question as how to deal with scarcity and finite resources.
3. The use of Carbon Capture Utilisation (CCU) or Carbon Capture Storage (CCS): here the approach consists of separating CO_2 from the exhaust gases of certain plants or from the air (carbon capture, CC) and then supplying it as a feedstock to other processes in which carbon or CO_2 is required (utilization, U) or alternatively to store (storage, S). CCU and CCS could become essential in some sectors in order to achieve greenhouse gas neutrality. This applies in particular to those industries with high percentage of process-related emissions, which cannot be avoided. This is the case for example for the cement industry, where only limited emission reductions could be achieved with a fuel switch.

The use of hydrogen also plays an important role, as a clean energy source. The aim in the future is to produce hydrogen in a greenhouse gas-neutral manner, for example through water electrolysis based on electricity from renewable sources. Currently, however, hydrogen is still obtained from natural gas, which results in CO_2 emissions.

[74] BMWK, 2020, „Wie wird die Produktion klimaneutral? Treibhausgasneutral bis 2050: dieses ambitionierte Ziel gibt das Klimaschutzpaket vor. Eine gewaltige Transformationsaufgabe für die Industrie" (https://www.bmwk.de/Redaktion/DE/Downloads/Monatsbericht/Monatsbericht-Themen/2020-03-im-fokus-wie-wird-die-produktion-klimaneutral.pdf?__blob=publicationFile&v=6).
[75] Project „Energiewende in der Industrie Potenziale, Kosten und Wechselwirkung mit dem Energiesektor": https://www.bmwk.de/Redaktion/DE/Artikel/Energie/energiewende-in-der-industrie.html

Finally, various other approaches are examined, for example to make recycling processes more effective. This can be an important starting point, especially in the steel industry.

The second big challenge faced by German EEIs in their decarbonisation commitments lies in the fact that capital-intensive production plants have long operational lifespans (often with depreciation periods of 50 to 70 years). This means that in the coming investment cycle, renewed investment in conventional technologies could lead to stranded assets, i.e. to the early decommissioning of assets that have not yet been fully depreciated, and to the associated economic losses.
The situation faced by the EEIs in Germany is alarming in this respect. In order to maintain current production levels, massive reinvestments into production plants will have to be made in the coming years. Some examples: by 2030, around 53 per cent of the blast furnaces in the steel industry, around 59 per cent of the steam crackers in the basic chemical industry and roughly 30 per cent of the cement kilns in the cement industry will need a reinvestment.
Companies will not make the necessary replacement investments if the long-term economic and regulatory conditions are uncertain. In light of increasing demands for climate protection, reinvesting in conventional, emission-intensive technologies faces a greater likelihood of being decommissioned early, increasing the risk associated with such endeavours. From the standpoint of companies as a rational economic actor, there are only two options: to invest in climate-neutral technologies in the next investment cycle, or to close down existing production plants at the end of their service lives and, if necessary, make new investments abroad, thus triggering massive job losses[76] (the carbon leakage phenomenon, describes in the previous chapters).

As illustrated above, technological potentials that could be harnessed to make the EEIs almost completely climate-neutral already exist today. But these technologies and production processes are still significantly more expensive today than conventional manufacturing processes and the additional costs cannot be passed on to customers because of fierce international competition. Therefore, to stimulate investment in these innovations now, industry actors need political signals that the government will actively support this transformation.
According to a study conducted by Agora Energiewende and Wuppertal Institute[77], the shift to low-carbon production processes requires a comprehensive new regulatory framework, with the following prerequisites:

- Industry actors need long-term, cross-party assurance that Germany will ensure internationally competitive energy prices for its EEIs.
- The new version of the EU state aid guidelines must be geared towards climate neutrality. National policy instruments to promote low-carbon technologies should not require individual approval from the European Commission, thus ensuring that the supplemental investment and operation costs associated with such technologies can be financed over the long term.
- Necessary infrastructure, including power lines, hydrogen pipelines and CCS infrastructure (pipelines and ports as well as safe CO_2 storage facilities) must be reliably available in good

[76] Agora Energiewende and Wuppertal Institute, 2019, “Climate-Neutral Industry (Executive Summary): Key Technologies and Policy Options for Steel, Chemicals and Cement”.
[77] *Ibidem*.

time. To this end, planning approval must be granted quickly; this will require adjusting permitting rules and associated appeal procedures.

While the above regulatory provisions are important prerequisites, by themselves they cannot ensure the success of the transformation. Additional political measures and policy instruments are needed to encourage the shift to low-carbon production process, as those developed by Agora Energiewende and Wuppertal Institute and listed below[78].

1. Carbon price floor with border carbon adjustment: this option foresees introducing an increasing carbon price floor to the EU ETS, in order to provide a predictable price incentive. In addition, a carbon tax would be levied on imports, and exports to regions without carbon prices would receive tax credit equal to CO_2 costs.
2. Carbon Contract for Difference (CfD): under this policy instrument, when investing in key low-carbon technologies, companies would receive project-related subsidy payments based on avoided CO_2 emissions, thereby reducing project risks for industry actors. The amount of subsidy funding would be determined through an auction. Over the long term, the ability to participate in the auction should be available to all companies.
3. Green financing instruments: this instrument foresees reducing financing costs for investments in low-carbon technologies, either by offering below-market interest rates or indemnifying creditors for potential losses when projects are at the final stages of technology development.
4. Climate surcharge on end products: to help refinance other policy instruments mentioned here, a special charge would be levied on selected materials (steel, plastic, aluminium and cement), irrespective of emissions associated with their production.
5. Carbon price on end products: when products are sold to the end consumer, a charge would be levied based on the carbon content of the materials, thus offsetting the cost disadvantage of low-carbon products. This charge revenue could then be used to finance other instruments.
6. Green public procurement: public-sector entities would be required to fulfil sustainability requirements i.e. when developing infrastructure (e.g. buildings, bridges and railways) and procuring vehicles. This would create reliable demand for sustainably produced basic materials and end products (especially steel, cement and vehicles).
7. Quota for low-carbon materials: producers of consumer goods would be obliged to use fixed shares of low-carbon materials in their end products, thus guaranteeing demand for low-carbon materials.
8. Green hydrogen quota: natural gas providers would be required to sell a certain share of green hydrogen, thus ensuring the expansion of power-to-x technologies on the road to long-term decarbonisation.
9. Changes in construction and product standards: regulations and standards would be fundamentally revised and continuously adapted in order to simplify material efficiency and substitution and the use of new building materials in construction (e.g. cement based on alternative binders).

[78] *Ibidem*.



10. Standards for recyclable products: manufacturers would be obliged to design products so that recycling is simplified in order to close material loops and to reduce carbon-intensive primary production.

In conclusion, the competitiveness of the economy remains a key issue for Germany as an industrial power. The key challenge is to create a regulatory and policy framework that ensures the necessary technology shift without jeopardizing international competitiveness, while ensuring that there is open-technology competition for the best path. In view of the long investment cycles in industry, the regulatory course must be set in the next few years and it will be crucially important to develop a coherent set of instruments.



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RE4INDUSTRY

100% Renewable Energies for Energy Intensive Industries

Grant Agreement Nº 952936

D3.1 - Ells Sector Status in Europe

Country Report – Greece

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Lead Beneficiary: CERTH

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Abbreviations

AN/CAN	Ammonium Nitrate / Calcium Ammonium Nitrate
AoG	Aluminium of Greece
EIIs	Energy Intensive Industries
ELTs	End of Life Tyres
EUA	European Union Allowance (right to emit 1 tCO_2-eq)
EU-ETS	EU Emission Trading Scheme
GHG	Greenhouse gas
NPK	Nitrogen Phosphorus Potassium
Scope 1 emissions	Direct GHG emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment
Scope 2 emissions	Scope 2 accounts for GHG emissions from the generation of purchased electricity, steam or other energy utilities consumed by the company.
Scope 3 emissions	Scope 3 emissions are a consequence of the (upstream and downstream) activities of the company, but occur from sources not owned or controlled by the company.
SRF/RDF	Solid Recovered Fuel/Refuse Derived Fuel

1 Introduction

The present report aims to provide an overview of the Energy Intensive Industries (EIIs) sector in Greece, with specific focus on the RE4Industry target sectors, i.e. Non-Ferrous metals, lime & cement, chemicals & fertilizers, steel, ceramics, and glass. Although Greece is not as heavily industrialized as other EU member states[1], there is a significant presence and economic activity of several large EIIs, as well as several smaller companies. In some specific sectors, or sub-sectors the activity of Greek companies is actually relevant even on the EU level.

In this chapter, a brief overview of the size of these sectors expressed in EU-ETS emissions is given. The next chapters provide a more detailed information, presenting the most relevant companies of each sectors and their progress regarding the decarbonisation of their production. It is important to mention that will be presented only the companies where takes place primary production.

Table 1: Overview of emissions of Greek EU-ETS sectors in 2020 and their development since 2015. (https://re4industry.eu/eiis-interactive-map/)

Sector	Operating installations	Mt CO_2 (2020)	% of all sectors	Mt CO_2 (2015)	Change (2015-2020)
Aluminium	2	1.367	4.31%	1.282	6.61%
Cement	6	4.709	14.84%	5.523	-14.74%
Lime	13	0.229	0.72%	0.234	-2.23%
Ceramics	11	0.113	0.36%	0.072	57.33%
Fertilizer	2	0.235	0.74%	0.282	-16.67%
Ferrous Metals	5	0.468	1.47%	0.938	-50.14%
Glass	1	0.047	0.15%	0.047	0.06%
Pulp and Paper	8	0.07	0.22%	0.109	-35.89%
Inorganic Chemicals	1	0.022	0.07%	0.025	-9.65%
Mineral Oil	4	5.248	16.54%	5.517	-4.88%
Other	14	0.191	0.60%	0.258	-25.69%
Other Calcination Products	1	0.183	0.58%	0.172	6.35%
Other Chemicals	0	0	0.00%	0	-
Other Non-Ferrous Metals	0	0	0.00%	0	-
Petrochemical	0	0	0.00%	0	-
Construction Materials	0	0	0.00%	0	-
Coke Ovens	0	0	0.00%	0	-
Hydrogen Production	0	0	0.00%	0	-
Power and Heat	39	18.845	59.40%	35.407	-46.78%
Total	**107**	**31.727**	**100.00%**	**49.865**	**-36.37%**

[1] The industrial sector in Greece amounted to 14.16 % of the national Gross Value Added (GVA), lower than the EU-27 average of 20.16 % (Source: Eurostat, Gross value added and income by A*10 industry breakdowns, [nama_10_a10])

Source: EU-ETS reporting as collected in https://re4industry.eu/eiis-interactive-map/, edited by CERTH

As shown in Table 1, the power and heat sectors are responsible for the largest share in the GHG emissions of the Greek EU-ETS sector, but they were able to reduce their emission by 16.56 Mt or 46.78% since 2015. Within the sectors focussed on in this report, the aluminium (1.367 Mt CO_2-eq in 2020) and cement (4.709 Mt-eq in 2020) are the largest contributors, as illustrated in **Error! Reference source not found.**. The ceramic industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015, however by observing the Figure 1, the sector has significantly decrease its CO_2 emissions since 2005.
Finally, in the period 2008-2010 there is a large fall in the CO_2 emissions of cement industry, which could easily assumed that is due to the economic crisis that faced Greece, which almost wiped out the construction industry and had as consequence the reduction of the cement production and therefore the reduction of the emissions in the production units.

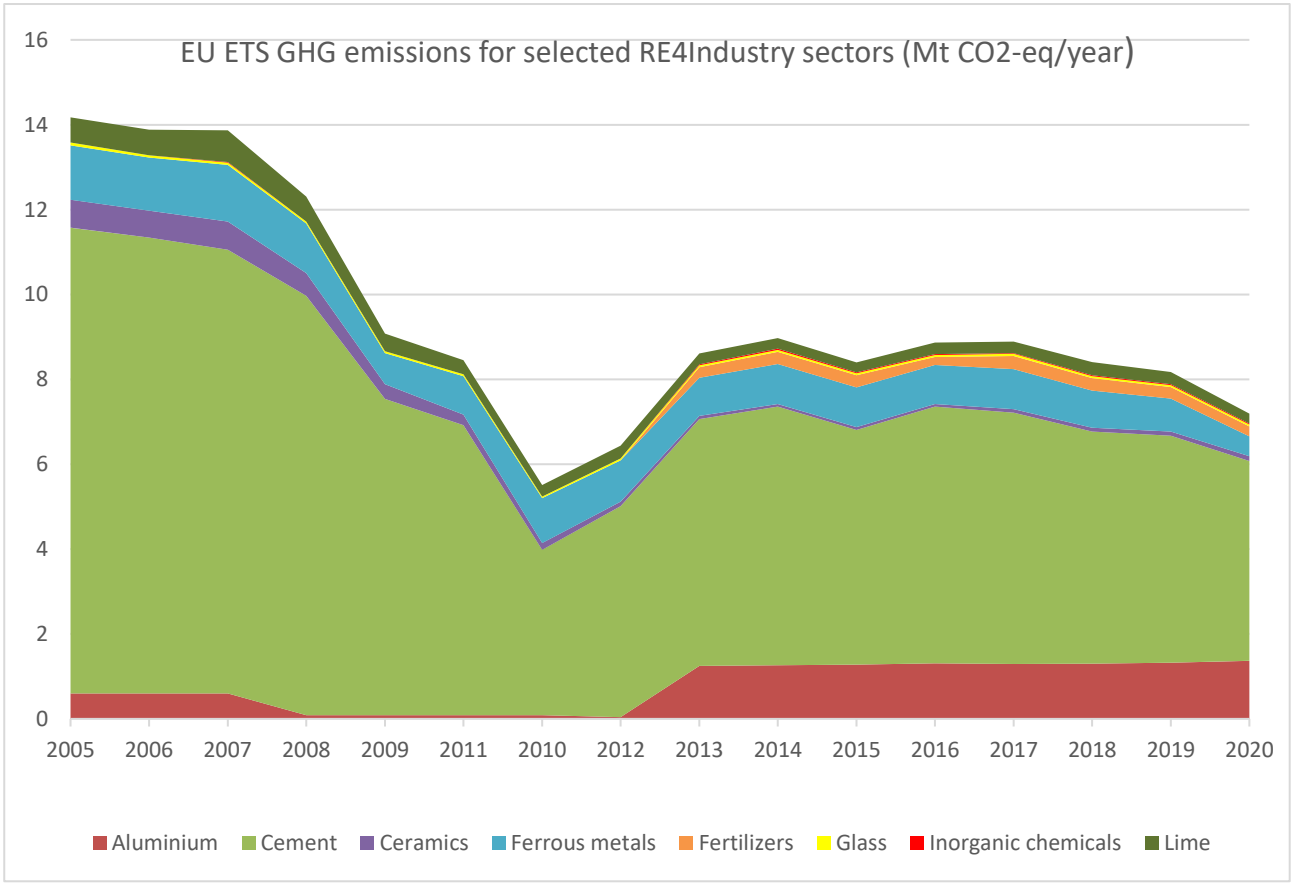


Figure 1 - EU ETS GHG emissions of selected RE4Industry sectors in Greece (https://re4industry.eu/eiis-interactive-map/)

2 Non-Ferrous metals

Aluminium

The Greek non-ferrous metals industry consists mainly of one primary aluminium production company and one processing industry.
The only one primary aluminium production company is Mytilineos thought Aluminium of Greece and it is the largest vertically integrated alumina and aluminium producer in the European Union, with an annual production capacity that exceeds 182,000 tons of aluminium and 820,000 tons of alumina.
The electricity needs of AoG correspond to around 320 MW, with an almost constant load profile. In 2020, the electricity consumption of the facility amounted to 2,840 GWh, corresponding to around 5.66 % of the total electricity consumption of Greece.

Table 2: Overview of companies active in the non-ferrous metals industry in Greece

Company	Location	Class Description	EU ETS CO_2 emission in 2020 (tCO_2)
ALUMINIUM OF GREECE(MYTINEOS)	Viotia	Primary aluminium production	1,260,158
ELVAL S.A.	Viotia	Rolling processing of aluminium	106,927
Total			**1,367,085**

Source: list of EU ETS companies (https://re4industry.eu/eiis-interactive-map/)

MYTILINEOS, Aluminium of Greece, Viotia

Aluminium of Greece (AoG) which is the metallurgy unit of MYTILINEOS is one of the largest industries in Greece. The industrial complex is located in Agios Nikolaos, Viotia, in close proximity to the bauxite deposit zones of Mountains Helikon, Parnassus and Giona. Covering a total area of 75 hectares, AoG is the only vertically integrated aluminium producer in Europe and possible even the only one in the world that houses all production and refining facilities under one site: alumina refinery, smelter, anode plant, power plants, casting house, red mud filtration unit and port facilities. The final products final products after foundry line are billets (124,000 t/a) and slabs (40,000 t/a).
Southeast of the aluminium plant, the Power & Gas Business Unit of MYTILINEOS operates a number of natural gas fired plants. In 2008, the first 334 MWe Combined Heat and Power (CHP) unit started its operations. Apart from producing electricity for the grid, the unit also provides steam used for the production of hydrated alumina, leading to a major reduction of the fuel oil consumption by AoG and associated GHG emissions. A 448.5 MWe CCGT started commercial operations in 2012, while one of the most modern CCGT units in Europe – with a capacity of 826 MWe - is expected to start commercial operations within 2022.
In February 2021, MYTILINEOS announced its formal commitment to sustainable operations according to ESG (Environment, Social and Government) performance indices and more specifically



for the Metallurgy BU, he company aims to establish a global benchmark in “Green Metallurgy” by reducing its absolute emissions by 65 % and its relative emissions (as measured per ton of aluminium produced) by 75 % by 2030. This goal is expected to be reached through increased production of secondary aluminium through the company subsidiary EPALME, as well as by measures aiming to decarbonize its electricity consumption.



Figure 2 -Major blocks of the AoG plant (https://www.mytilineos.gr/, edited by CERTH)

In February 2021, MYTILINEOS also announced the first corporate PPA (Power Purchase Agreement) in the Greek electricity market. The PPA is expected to be initiated during 2023 and concerns a total capacity of 200 MW from PV parks owned by EGNATIA Group. The price will be 33 EUR/MWh and the contract will have a duration of 10+5 years. Along with this PPA, MYTILINEOS also announced the acquisition of a 1.48 GW PV project portfolio at a mature licensing stage (also from EGNATIA Group) as well as a pipeline portfolio of 25 energy storage projects.
The RE4Industry project also supports the decarbonisation efforts of the Metallurgy BU of MYTILINEOS through the investigation of alternative renewable energy options for the decarbonisation of the thermal energy demands of the Aluminium of Greece plant – currently, primarily covered through natural gas.

Conclusion
Primary aluminium production is highly electro-intensive process, this points that non-ferrous metals industry is extremely sensitive to electricity prices, which affect its economic performance and competitiveness.

3 Cement & Lime

Cement

Cement production is a very dynamic industrial sector in Greece. The Greek cement industry employs about 3,000 persons and is concentrated in three companies: HERACLES (a member of Holcim Group), TITAN and Halyps (a member of Heidelberg Cement Group). Their annual production capacity is 6.7, 6.9 and 1.0 Mt/y respectively.

Table 3: Overview of companies active in the cement industry in Greece

Company	Location	Class Description	EU ETS CO_2 emission in 2020 (tCO_2)
TITAN Cement International SA	Kamari, Viotia	Cement Manufacturing	1,334,570
HERACLES, Holcim	Volos	Cement Manufacturing	1,098,189
HERACLES, Holcim	Milaki, Evia	Cement Manufacturing	858,500
TITAN Cement International SA	Thessaloniki	Cement Manufacturing	603,035
TITAN Cement International SA	Drepano, Patra	Cement Manufacturing	569,036
HALYPS BUILDING MATERIALS S.A	Aspropyrgos, Attiki	Cement Manufacturing	245,347
Total			**4,708,677**

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

The Hellenic Cement Industry Association (HCIA) represents the interests of the cement industry in Greece and is a member of the European Cement Association (CEMBUREAU).

Table 4 - Current and future SRD/RDF use capacity by the Greek cement industry (source: HCIA)

Cement plant	Current SRF/RDF use capacity at full production (t/y)	Future SRF/RDF use capacity at full production (t/y), following investments and licensing
Volos	80,000	250,000
Milaki (Evia)	50,000	150,000
Kamari (Viotia)	80,000	260,000
Drepano (Patra)	-	70,000
Thessaloniki	40,000	110,000
Aspropyrgos	20,000	25,000
Total	**270,000**	**815,000**

HERACLES, HOLCIM GROUP

Heracles Group member of Holcim, founded in 1911, is one of the two largest cement production companies in Greece with an annual turnover of 188.159 m€ in 2020, employing 609 directly. Heracles has two cement production plants in Volos and Milaki (Evia) but also port facilities that serve the internal market and strengthen the export activity in the wider Mediterranean region. In addition, it has active quarries and mines throughout Greece and distribution centers all over the country.

In 2020, HERACLES reported[2] that the share of alternative fuels, including biomass, in its total energy consumption reached 27.7 %, more specifically, 130,000 tons of alternative fuels were used, leading to a reduction of 85,000 tons of CO_2. This was achieved through a series of investment projects at the facilities in Volos and Milaki. Implemented in 2020, the 2 m€ investment project in Milaki already managed to utilize 15,000t of biomass and has capacity to substitute up to 20,000 t/y of fossil fuels with 75,000 t/y of urban prunings, agricultural residues and other biomass fractions. According to its CEO, the company aims to reach a 50 % share of alternative fuels in 2023.

TITAN Cement International SA

TITAN is one of the two largest cement production companies in Greece with an annual turnover of 286.2m € in 2020, employing 1.142 directly. TITAN has three cement production plants in Greece, in Kamari (Viotia), Drepano (Patra) and Thessaloniki, but also has a strong global presence (America, Europe).

Their commitment[3] regarding the decarbonisation on the cement plants are to reduce until 2030 their scope 1 emissions by 35% and scope 2 emissions by 45%, both in comparison to 1990 level. In addition, TITAN committed to increase the annual investment in Research & Innovation to €20m and to drive down further the CO_2 footprint in order to succeed carbon-neutral concrete by 2050.

In 2020, the net CO_2 emissions reached 674kgCO_2/t of cement. The Thessaloniki cement plant extended its environmental permit to facilitate the use of SRF/RDF from municipal solid waste.

Finally, TITAN participates in the RECODE research project, which involves the installation of a pilot unit at Kamari cement plant in Greece for the capture of CO_2 and its conversion to value-added chemicals.

Conclusion

The cement industry is very energy intensive. The changing of the raw material composition or the reducing of share of Portland clinker is highly relevant. In addition, cement kilns are suitable for co-combustion of low-quality biomass such as sewage sludge.

[2] https://www.lafarge.gr/sites/greece/files/atoms/files/ekthesi_aeiforias_2020.pdf
[3] https://www.titan-cement.com/TITAN_Cement_Group_IAR_2020_EN.pdf

Lime

Currently, lime is used in a wide range of applications and is made by heating calcium carbonate ($CaCO_3$), leading to the release of CO_2 and the production of lime (calcium oxide, CaO). Energy costs represent 40% of the production costs and depend on the energy efficiency of the kiln, as well as on the type of and price of fuels[4].
In Greece, the lime industry emits about 229,000tn CO_2 , of which 75% are process emissions. It consists of 13 operating units and the annual production is around 400-500kt. Thermal energy demands covered primarily by petcoke. Some installations, usually smaller mainly in Southern Greece use biomass (exhausted olive cake). Below they are presenting the most relevant ones that contribute the most to the CO_2 emissions.

Table 5: Overview of most relevant companies active in the lime industry in Greece

Company	Location	Class Description	GHG emission 2020
CaO HELLAS	Volos	Lime manufacturing	60,979
DOMIKI P. PAVLIDES S.A.	Plagiari, Pella	Lime manufacturing	51,048
CAO HELLAS	Thessaloniki	Lime manufacturing	35,424
K. ΡΑΪΚΟΣ Α.Ε.	Aspropyrgos, Attiki	Lime manufacturing	35,119
Total			**182,570**

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

The Hellenic Lime Association (HLA) represents the interests of the lime industry in Greece and is a member of the European Lime Association (EuLA).

CaO HELLAS

Cao HELLAS is the largest lime industry in Greece. It I founded in 1980 by Evangelos Ampas and the aim of the group is the production of specialized high quality lime products. The company owns three facilities with different capabilities and products. The first facility is located in Thessaloniki and successfully launched in the early 80's. The installation consists of a lime production plant, with a capacity of 50,000 t/y. In addition, there is a hydrated lime production line, with a capacity of 30,000 t/y. Both production lines are accompanied with air classifier and grinding system. The second facility, in Thessaloniki, was established in 1999 with the aim of specializing in the field of aluminium and steel industries. It consists of modern production and control systems and has a capacity of 450 t/day. The flexible and fully automated production system allows the production of different lime products in different sizes. In 2006, was established a second high-temperature lime kiln for the production of dolomitic lime and specialized products for steelwork industry. In this unit, there is also a hydrated lime plant of 5 t/hour. Finally, in the last facility in Amynteo operating since 2005, was established to support the growing demand for lime products in the area. Specifically, the Amyntaio

[4] https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Technical report-by-Ecofys_0.pdf

facility mostly operates to fulfil the needs of Public Power Corporation and agricultural demand of north Greece and neighbouring countries.
All the three installations (Volos, Thessaloniki and Amynteo) which have the latest technology equipment, with PFRK type blast furnaces (parallel flow regenerative kiln). The fuels that are used are natural gas, liquefied petroleum gas, biomass and petroleum coke (Pet-Coke).
In Thessaloniki, plant there is also a well-equipped laboratory for research, development and quality control. This laboratory permits CaO HELLAS to participate in co-financed EU research programs. The main object of the research is the development of decarbonisation technologies with the ultimate goal of investing in advanced environmental protection technologies. Towards this scope, CaO HELLAS, is participating in the following projects:

- CAPSOL (Design Technologies for Multi-scale Innovation and Integration in Post-Combustion CO_2 Capture: From Molecules to Unit Operations and Integrated Plants) (https://cordis.europa.eu/project/rcn/100978/reporting/en)
- ROLLINCAP Systematic Design and Testing of Advanced Rotating Packed Bed Processes and Phase-Change Solvents for Intensified Post-Combustion CO_2 Capture. (http://www.rolincap-project.eu/)
- NANOCAP, capture of CO_2 and use for the industrial production of nanoparticles of precipitated calcium carbonate. (http://nanocap.cperi.certh.gr/)
- ANICA, Advanced Indirectly heated Carbonate Looping Process to decrease CO_2 capture cost and achieve net negative e CO_2 emissions. (https://act-anica.eu/)

DOMIKI P. PAVLIDES S.A.

Domiki P. Pavlidis S.A. is a member of the Group of Companies Prodromos Pavlidis. The company is installed in Plagiari, Giannitsa, with privately owned area next to the limestone quarry of the Group and specializes in the production of high quality lime and hydrated lime. The industry consists of two units, the lime and hydrated lime production units, with a daily gross capacity of 300 t. The annual CO_2 emissions in 2020 reached 51,048t making DOMIKI P. PAVLIDES S.A. the second most CO_2 intensive lime industry in Greece.

RAIKOS S.A.

Raikos S.A. is a smaller lime production company, located in Aspropyrgos, Attiki. It was founded in the early 1960's by Konstantinos Raikos and has production capacity of 350 tons daily. Regarding the decarbonisation targets and circular economy, the company uses crumb rubber from ELTS as an alternative fuel, harnessing a waste flow, which is significantly cheaper as fuel in contrary to others and which produces lower amounts of CO_2 emissions.

4 Chemicals & Fertilizers

Chemicals

In Greece, the chemical industry is small. The only one industry at this time that is active is TOSOH HELLAS and it under the sub-sector of inorganic chemicals.

Table 6: Overview of companies active in the inorganic chemicals industry in Greece

Company	Location	Class Description	GHG emission 2020
TOSOH HELLAS	Sindos,Thessaloniki	Production of electrolytic manganese dioxide	22,329

TOSOH HELLAS S.A.

Tosoh Hellas S.A. was founded in 1973 under the corporate name “Tekkosha Hellas S.A.” by the Japanese firms Tekkosha and Mitsubishi Corporation. In 1987, the company renamed to the current corporate name of the Japanese group Tosoh Corporation, which is a one of the most big producer and suppliers of inorganic chemicals, petrochemicals and specialist materials. In Greece, the facilities are located in Sindos, the Industrial Area of Thessaloniki and the company’s commercial exports account for 1.5 M €.
Tosoh Hellas has been active since 1976 in the production of electrolytic manganese dioxide (commercial known as EMD), an essential key component for the production of dry cells (batteries). Tosoh Hellas S.A. is the largest producer of electrolytic manganese dioxide (EMD) in Europe, supplying the global batteries market and acting as the primary supplier for leading European manufacturers of alkaline batteries. The production accounts for 40% (24,000t) of the Group’s total EMD production capacity and its activity is 100% exporting.
Tosoh Hellas spend every year over 1 M € for environmental purposes that promote circular economy solutions and has succeed to reduce the CO_2 emissions about 60% since 2003.

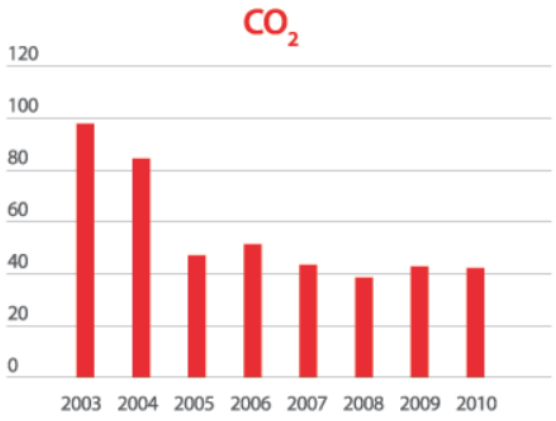


Figure 3 - CO_2 Emissions TOSOH HELLAS, period 2003-2010[5]

Fertilizers

The industry of fertilizers in Greece is also a small market. In Table 6 there are the two companies

[5] https://www.tosoh-hellas.gr/environment/programs

that produce fertilizers. They are both located in Nea Karvali, Kavala , in the same geographic area and the sum of CO_2 emissions reaches 235t in 2020. Hellagrolip S.A., since 2021 is under the brand name Kavala Fertilizers.

Table 7: Overview of companies active in the fertilizer industry in Greece

Company	Location	Class Description	Carbon emission in 2020
HELLAGROLIP S.A.	Nea Karvali, Kavala	chemicals and nitrogenous fertilizers	215,334
PFIC LTD	Nea Karvali, Kavala	Fertilisers and nitrogen compounds	19,809
Total			**235,143**

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

Both fertilizers industries in Greece are members of the Fertilizers Europe.

Kavala Fertilizers Ltd

KAVALA FERTILIZERS LTD is the only producer of nitrogenous fertilizers in Greece. Inside the company, there is an ammonia plant (capacity 165,000t), two sulphuric acid plants (total capacity 430,000t), a nitric acid plant (capacity 230,00t), an ammonium nitrate solution plant (capacity 280,000t) and a nitrogenous fertilizers (AN/CAN) plant. In addition, there is four turbogenerators (installed power 21.218 MW) for combined production of heat and power from waste heat without use of fuel.Finally, Kavala Fertilizers houses port facilities.
Regarding the production of ammonia the fuel used is natural gas and it is planned to reduce the CO_2 emission by storing the CO_2 underground and by reducing the energy consumption via composition under atmospheric pressure. In the nitrogenous fertilizers plant, they do not use fuels for the drying process and there are planning to recover heat from gases for district heating of buildings. Finally in the nitric acid plant use direct energy from co-generation (turboset)

Table 8 - Decarbonisation actions & plans of Kavala Fertilizers Ltd

Plant	Decarbonisation actions applied	Future Decarbonisation plans
Ammonia	Natural gas	• Underground CO_2 storing • Composition under atmospheric pressure (lower energy consumption)
Nitric acid plant	Direct mechanical co-generation (turboset)	
Nitrogenous fertilizers plant	Drying process without fuels	Heat recovery for district heating

PFIC Ltd

PFIC Ltd is the second fertilizers producer in Greece with significant lower CO_2 emissions. Produces

phosphoric acid and complex NPK fertilizers. The Phosphoric Acid Plant has a capacity of 75,000t and the three Complex (NPK) Fertilizers Plants have total capacity of 750,000t. In the facility there is also an autonomous private port for loading/unloading products and raw materials.

Conclusion

The chemical and fertiliser industries are particularly dependent on green hydrogen in order to decarbonise their production processes. If green hydrogen would be available, it could change these industries in suppliers of green fuels and processes, like for instance the selling of green ammonia (produced by green hydrogen) as shipping fuel.

5 Ferrous metals

In Table 9 are presents the active ferrous industries in the Greece. The first one and the most carbon intensive is LARCO GMMSA that produces ferronickel. The others are steel industries that do either secondary steel production by scrap iron smelting or rolling and wire processing.

Table 9: Overview of companies active in the ferrous metal industry in Greece

Company	Location	Class Description	EU ETS CO_2 emission in 2020 (tCO_2)
LARCO GMMSA	Larimna, Fthiotida	Granulated ferronickel	338,485
SOVEL S.A.	Almyros, Magnissia	Rolling processing, wire mesh production	49,098
HELLENIC HALYVOURGIA	Velestino, Volos	Secondary steel production / production of semi-finished product (billet)	31,585
HELLENIC HALYVOURGIA	Volos	Rolling processing, wire mesh production	25,240
SIDENOR STEEL INDUSTRY S.A.	Thessaloniki	SD reinforcing steel. Wire rod	23,161
Total			**467,569**

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

LARCO GMMSA

LARCO is a Greek mining and metallurgical company established by Bodossakis Athansiadis in 1963. LARCO produces ferronickel and in fact was the first company that bring granulated ferronickel to the market.

The annual turnover is about 350 million euros, while employing around 1200 people. The company has a purely export character with 55.2% of its shares have been transferred from the Greek State to the Hellenic Republic Asset Development Fund S.A. (HRADF), while 33.4% of the shares are held by the National Bank and 11.4% by PPC. Larco has been under special management status since February 2020 and is expected to be sold to a new owner.

The company has a rich real estate portfolio. Its assets include mines in the area of Evia, Neo Kokkino in Viotia, Kastoria and Servia in Kozani, as well as a metallurgical plant in Larymna in Fthiotida. Another strategically important asset is the possession of the port in Larymna plant. In

addition, it has also an approved landfill in the area of Larymna, which was built to dispose slag, one of the by-products of metallurgical processes, but has not yet been utilized.
Apart from the main product, which is the ferronickel Larco has some other by-products. The first one of them is the slag that is produced during the metallurgical processes and can be used as sand blasting material and due to its pozzolanic properties (active SiO_2), is suitable for utilization in the production of cement. The second one is the aggregates, limestone (mostly) and spilite (volcanic rock), that are by-products of the nickel-iron ore mining at the company's mines.
The annual ferronickel production is around 25kt with the 18-22% used in steel industry. The basic production line consists of 4 rotary kilns, 5 electrical furnaces and 2 OBM-type converters, with a capacity of 50 tons of metal each. There are also secondary installations, such as 2 units for the production of oxygen and nitrogen, grinding units, and magnetic separation units. The plant operates 24 hours a day, 365 days a year, producing high-purity, low-carbon ferronickel granules, used exclusively in stainless steel production.
The typical energy consumption of the plant is 1,300 GWh/a of electricity and 2,450 GWh/a of heat power. The fuel used for the production are hard coal (300kt/a), lignite (300kt/a), petcoke (25kt/a) and HFO (40kt/a).
Finally, as mentioned before the company is currently under call of privatization so it is estimated that an investment of 200M€ is needed for environmental upgrade and 400M€ are needed for switch to hydrometallurgy (production of nickel and cobalt).
Of special value are also the licenses received by the LARCO subsidiary, LARCO Energeiaki, in collaboration with Hellenic Petroleum (ELPE), for the installation of photovoltaic parks of several tens of MW in privately owned areas of LARCO in Kastoria, Kozani, Fthiotida and Viotia.

6 Ceramics & Glass

Ceramics

The ceramics industry in Greece consists of 11 companies and produced 113kt CO_2 emissions in 2020. One of these companies, the "***Northern Greece Ceramics***" produces almost the half CO_2 emissions of them. An important point to mention is that this sector showed the largest increase in carbon dioxide emissions since 2015 with percentages reaching 57%. However, the ceramic sector is a small sector in Greece.

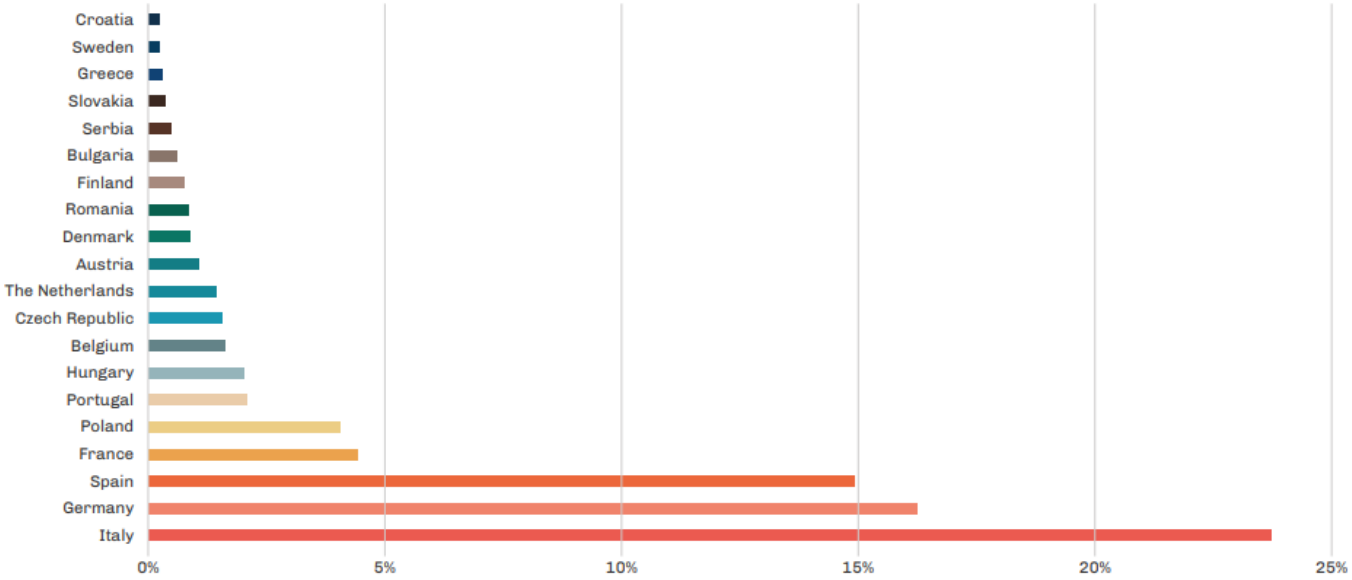


Figure 4 - Percentage of production value by European country (eu27) in 2020, Source: Eurostat, Cerame-unie)

Table 10: Overview of companies active in the ceramics industry in Greece

Company	Location	Class Description	Carbon emission in 2020
NORTHERN GREECE CERAMICS	Nea Santa, Kilkis	Bricks, Roof tiles, Ceramic Powder,Chimneys	54,904
VAVOULIOTIS	Schimatari, Viotia	Bricks	15,975
AKEK S.A.	Heraklion, Crete	Bricks, Roof tiles, Ceramic Shard, Refractory Bricks	10,851
ALPHA KERAMICA S.A.	Larissa	Brick & Structural Clay Tile	9,756
PANAGIOTOPOULOS S.A	Douneika, Ilia	Bricks, Roof Tiles & Ceramic Powder	6,521
VAVOULIOTIS	Vassiliko, Evia	Roof tiles	5,433
BRICKWORKS D.I. KOKKINOGENIS S.A.	Aspropirgos, Attiki	Bricks	4,899
NIKOU S.A.	Koritiani, Igoumenitsa	Bricks	1,763
MALIOURIS GROUP	Halastra, Thessaloniki	Bricks, Tiles	1,469
MITSIADIS S.A.	Larissa	Bricks	1,126
RETHIMNIOTIKI TOUVLOPIIA	Rethimno, Crete	Bricks	719
Total			**113,416**

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

The Association Greek Heavy Clay represents the interests of the ceramic industry in Greece and is a member of the European Ceramic Industry Association (Ceramie-Unie).

According to Ceramie Unie, emissions linked to ceramics production can be broken down into three main categories:
• Fuel combustion for drying and heating process.
• Process emissions generated by mineralogical transformation of the clay.
• Indirect emissions, mainly from electricity production.

In Greece, the produced ceramics are mainly bricks and tiles, the process emissions of this category reaches the 30% of total emissions and the rest are the emissions from fuel combustion and the indirect emissions (around 19%) has significant smaller share.
Based on the Roadmap to 2050[6] and considering that the target is the fuel combustion emissions and indirect emission to be lowered, the Greek ceramic industry will follow accordingly. The solutions that are more applicable up until 2030 is the use of renewable energy such as biomass or biofuels but also the use of heat pumps. Regarding the process emissions there could be a reduction of carbon-containing additives, dematerialisation (smaller quantities of raw materials for the same use). Finally, the reuse and recycling is another mean to reduce the CO_2 emissions from the primary production of ceramics. To this direction the biggest ceramics industry in Greece, the Northern Greece Ceramics has already installed a cogeneration plant for the production of electricity and heat (CHP), with 4.356 MW thermal output.

Glass

Table 11 shows that there is only one glass producer fall under EU-ETS that emits 47.3kt of CO_2-equivalents in 2020. Since 2015, the glass industry has remained stable regarding its CO_2 emissions.

Table 11: Overview of companies active in the glass industry in Greece

Company	Location	Class Description	Carbon emission in 2020
YIOULA GLASSWORKS S.A.	Egaleo, Attiki	Glass manufacturing	47,285

Source: list of EU ETS companies, (https://re4industry.eu/eiis-interactive-map/)

The Yioula Glassworks S.A. was sold in 2017 to the Portuguese glass industry “BA Glass Group” and is the only glass industry that is active today in Greece. It manufactures glass containers and tableware.
The BA Glass Groups goals are in line with the decarbonisation goals of Europe, which means that they have set the goal to became carbon neutral. For this purpose in 2020 CO_2 emissions decreased 1.9% when compared to 2019 (scope 1)[7].In particular the target is to reduce the usage of natural gas by replacing it with electricity, and use a minimum of 70% of electricity from renewable sources. To this direction, in order to use renewable sources of energy, the industry under FEVE(The

[6] Ceramie-unie - Ceramic-Roadmap to 2050
[7] BA 2020 annual report -EN

European Container Glass Federation) coordination, aims to develop a hybrid furnace capable of increasing the usage of electricity up to 80% of the total energy consumption. Another option to reduce the CO_2 emissions is the light-weighting of the bottles and jars. In 2020, the light-weighted products enabled to save more than 8,400 tons of CO_2 (Scope 1 and 2). Finally, the glass industry has been trying to replace the use of soda ash, a raw material that generates CO_2 when melted and which is the second-largest source of CO_2 emissions, with recycled glass for many years.

7 RE uptake – challenges and potential measures

Decarbonizing electricity – Renewable PPAs

High electricity prices is a major issue for the Greek EII sector. UNICEN – the Hellenic Union of Industrial Consumers of Energy – argues that the high electricity prices in Greece are a more structural issue, being heavily affected by the market organization. The Association has proposed a series of measures aiming to reform the Greek wholesale electricity market8, among which is the expansion of renewable Power Purchase Agreements (PPAs).

Although the cost of electricity from renewable electricity sources is constantly decreasing and in many cases has become competitive with fossil fuel options, the intermittent character of wind and solar energy requires that additional shaping and firming costs need to be taken into account for the renewable electricity sourcing and these pose additional risks for EIIs.

In order to solve this issue, the **"Green Pool"** concept has been proposed in a study commissioned by MYTILINEOS9. In brief, the concept foresees that EIIs invest in new RESe production capacity, the production of which is aggregated trough the Green Pool, reducing the overall shaping and firming costs. The renewable electricity can be distributed to the EIIs on the basis of the renewable generation capacity they have brought into the pool. Any remaining shaping and firming costs can be subsidized through funds available from the Recovery and Resilience Facility.

The Green Pool has been adopted by the Greek Government, becoming the basis of a proposal for the support of the EIIs sector in Greece. In early 2022, negotiations with the European Commission regarding the approval of the scheme are still ongoing. YPEN – the Ministry of Environment and Energy – anticipates the scheme to be launched in 2022, with an initial aim to cover 20 % of the EIIs' electricity demand through renewable PPAs. The anticipated level of public support is around 15 €/MWh.

Decarbonizing heat – biomass and renewable gases

On the one hand, the recent price hikes of both natural gas and CO_2 are actually a driver for decarbonisation all over Europe. On the other hand, EIIs are highly sensitive to energy costs and such increases can often make them to stop production altogether rather than switching to new alternatives.

Social opposition to renewable energy projects

Significant **social opposition** against several renewable energy projects in Greece has often been

[8] https://unicen.gr/en/%ce%bfur-priorities/
[9] https://enervis.de/wp-content/uploads/2021/04/enervis_MYTILINEOS_Green-Pool_Final_Report_study_03_2021.pdf

detected. This opposition most strongly materializes against wind farms that have been set for establishment in mountainous and/or touristic areas of Greece. To our knowledge, this activity has not directly impacted renewable electricity projects that have been planned with the explicit purpose to decarbonize the electricity supply to EIIs in Greece.

More specific to the EII sector is the social opposition to initiatives related to the utilization of alternative, waste-derived fuels in the cement industry. The opposition is more evident in the Volos cement plant[10], due to its close proximity to a big population center and local air emissions issues. It should be noted that such issues are common in waste-to-energy projects in most countries of the world. Moreover, it would appear that there is less opposition to plans related to the utilization of "green waste" fractions, such as urban prunings, or other biomass assortments originating from post – fire forest management activities.

Company size and financial limitations

As a final note, it should be noted that many Greek EIIs are actually small or medium sized companies, with limited capacities to implement investments related to renewable energy uptake. On the other hand, it is evident that Greek companies with a strong position in their sectors are in fact willing to implement investments related to increased uptake of renewable energy.

[10] https://www.cemnet.com/News/story/169203/srf-factory-planned-at-volos.html



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RE4INDUSTRY

100% Renewable Energies for Energy Intensive Industries

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Country Report – Netherlands

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Abbreviations

EIIs	Energy Intensive Industries
EUA	European Union Allowance (right to emit 1 tCO_2-eq)
EU-ETS	EU Emission Trading Scheme
GHG	Greenhouse gas
Scope 1 emissions	Direct GHG emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment
Scope 2 emissions	Scope 2 accounts for GHG emissions from the generation of purchased electricity, steam or other energy utilities consumed by the company.
Scope 3 emissions	Scope 3 emissions are a consequence of the (upstream and downstream) activities of the company, but occur from sources not owned or controlled by the company.

1 Introduction

This report gives an overview of the status of the current and planned application of renewable energy in the energy intensive industry (EII) in the Netherlands, with specific focus on the RE4Industry target sectors, i.e. Non-Ferrous metals, lime & cement, chemicals & fertilizers, steel, ceramics, and glass. In this chapter, we give a brief overview of the size of these sectors expressed in EU-ETS emissions. The next chapters provide more detailed information on renewable energy production and where appropriate energy saving measures are taken and planned by the most relevant companies of these sectors.

Table 1: Overview of emissions of the Dutch EU-ETS sectors in 2020 and their development since 2015.

Sector	Mton CO_2-eq in 2020	% of all sectors	Mton CO_2-eq increase since 2015	% Increase since 2015
Aluminum	0.32	0.4%	0.08	34%
Other Non-Ferrous Metals	0.05	0.1%	-0.01	-22%
Cement	0.01	0.02%	-0.40	-97%
Other Chemicals	9.25	12.5%	0.80	9%
Fertilizer	5.07	6.8%	-0.52	-9%
Ceramics	0.17	0.2%	0.01	6%
Ferrous Metals	5.80	7.8%	-0.53	-8%
Glass	0.42	0.6%	-0.12	-22%
Construction Materials	0.38	0.5%	0.02	5%
Hydrogen Production	2.04	2.7%	0.16	9%
Inorganic Chemicals	0.60	0.8%	-0.07	-11%
Mineral Oil	10.25	13.8%	-0.91	-8%
Other	4.60	6.2%	-0.93	-17%
Petrochemical	0.49	0.7%	-0.17	-26%
Power and Heat	33.68	45.4%	-17.32	-34%
Pulp and Paper	0.98	1.3%	-0.10	-9%
Total	**74.11**	**100.0%**	**-20.00**	**-21%**

Focus of this report

Source: EU-ETS reporting as collected in https://re4industry.eu/eiis-interactive-map/, edited by BTG

As shown in Table 1, the power and heat sectors are responsible for the largest share in the GHG emissions of the Dutch EU-ETS sector, but were able to reduce their emission by 17.32 Mton or 34% since 2015. Within the sectors focussed on in this report, the other-chemicals (9.25 Mton CO_2-eq in 2020, ferrous metals (5.80 Mton) and fertiliser industry (5.07 Mton) are the largest contributors, as illustrated in Figure 1. The fertilizer industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015; though these emissions stabilised from 2015 onwards. The large decrease of the emissions in the cement industry is directly related to the closure of the ENCI Maastricht plant, that produced Portland clinker from its own marl mine.

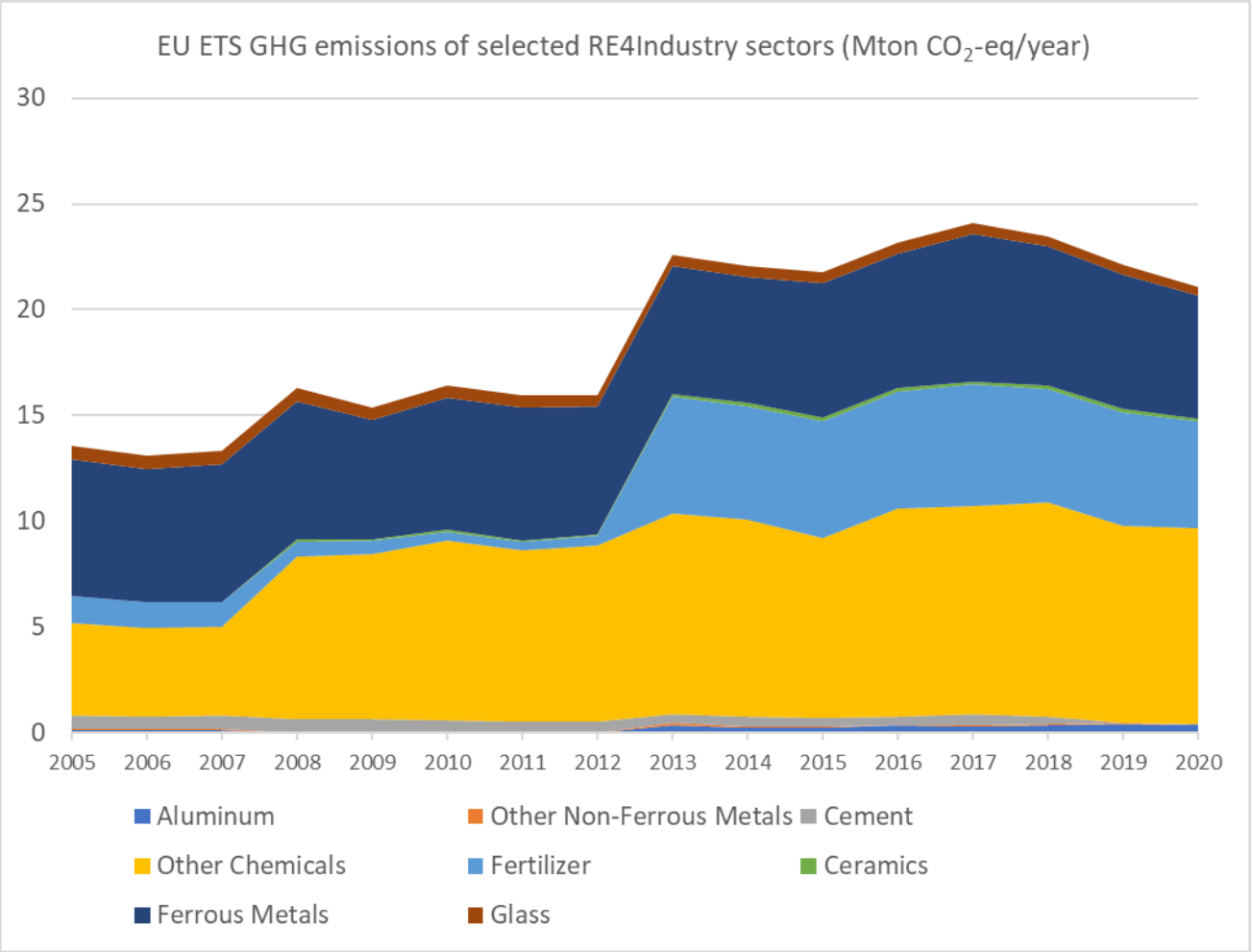


Figure 1: EU ETS GHG emissions of selected RE4Industry sectors in the Netherlands

2 Non-Ferrous metals

The Dutch non-ferrous metals industry consists mainly of aluminium production and processing related industries. Aldel in the North of the Netherlands (Delfzijl/Farmsum) is the only primary aluminium producer of the Netherlands. At full capacity it uses 200 MW electricity. Recent high electricity prices of 4500 €/tonne aluminium combined with sales price of 2500 €/tonne caused severe problems, but in December 2021 the company was saved from bankruptcy[1]. Zeeland Aluminium Company (Zalco) stopped aluminium production in 2011 but is still active as foundry[2]. E-MAX sells aluminium profiles and billets in various alloys, using a high share of recycled aluminium. Alumimium & Chemie Rotterdam is a supplier for the aluminium industry but has recently ceased production.

Table 2: Overview of companies active in the non-ferrous metals industry in the Netherlands

Company	Location	ClassDescription	EU ETS CO_2 emission in 2020 (tCO_2)
DAMCO Aluminium Delfzijl Coöperatie U.A. (Aldel)	Farmsum	Aluminium production	151,125
Century Aluminum Vlissingen BV	Ritthem	Aluminium production	57,507
Zalco B.V.	Vlissingen-Oost	Aluminium production	14,636
E-max Remelt	Kerkrade	Casting of light metals	20,009
Aluminium & Chemie Rotterdam B.V.	Botlek Rotterdam	Aluminium production	95,413
Nyrstar Budel B.V.	Budel	Lead, zinc and tin production	26,153

Source: list of EU ETS companies (tool Manolis)

DAMCO (Aldel), Farmsum

Aldel is involved in several renewable energy projects. Aldel plays a role as “virtual battery” by using more electricity during hours with high solar and wind electricity and vice versa, improving grid stability[3]. Furthermore, Aldel investigates the use of 50,000 m^3 roof space and 70,000 ground space for about 18-20 MW solar PV capacity[4]. Moreover, it offered connection of 21.5 MW of solar parks of third parties, directly to the power grid of Aldel, avoiding capacity problems on the national grid. Besides these plans, Aldel executes energy saving measures like installation of LED lighting and installation of a speed-controlled compressor for compressed air.

ZALCO, Ritthem

Zalco is investigating the possibility of installing a wind turbine in collaboration with the local energy supplier. Moreover, they stress their efforts for energy savings as confirmed in a multiannual

[1] https://nos.nl/artikel/2408773-aluminiumfabriek-aldel-gered-maar-120-mensen-verliezen-hun-baan
[2] https://zalco.nl/nl/geschiedenis
[3] https://aldel.nl/green-strategy/project-virtuele-batterij/
[4] https://aldel.nl/green-strategy/project-zonnecellen/

agreement with the state. They also point to the fact that they use a large proportion of recycled material for its production[5].

E-MAX Remelt, Kerkrade

E-MAX emphasises that they use as much as possible recycled aluminium saves up to 95% energy compared to new aluminium. E-max branches generate part of their own electricity demand using solar panels.

Conclusion

Primary aluminium production is very electricity intensive. This generates opportunities for large scale use of wind power and net balancing, supplemented by solar PV. High electricity prices make the future of aluminium production very uncertain, which could cause delays in renewable energy investments. Optimal recycling of aluminium is probably the most efficient way to lower the carbon footprint of the aluminium processing industry.

3 Lime & Cement

Table 3 gives an overview of EU-ETS companies active in the lime and cement industry in the Netherlands.

Table 3: Overview of companies active in the cement industry in the Netherlands

Company	Location	ClassDescription	EU ETS CO_2 emission in 2020 (tCO_2)
ENCI B.V., vestiging IJmuiden	Velsen Noord	Manufacture of cement	12,197
ENCI B.V., vestiging Maastricht	Maastricht	Manufacture of cement	Closed (474,200 in 2017)
Suiker Unie, productielocatie Vierverlaten	GRONINGEN	Manufacture of sugar, byproduct Betacal contains lime	112,426
Suiker Unie fabriek Dinteloord	DINTELOORD	Manufacture of sugar, byproduct Betacal contains lime	115,201

Source: list of EU ETS companies

Lime

The Netherlands has a very small lime industry. Yearly, 200 ktonnes of lime is mined by (non ETS firm and therefore not found in Table 3) Sibalco in Winterswijk. After 2018 ENCI ceased lime mining in Maastricht[6].

The sugar industry is a consumer of calcium, making a (by) product out of it. The Netherlands has a

[5] https://zalco.nl/nl/veiligheid-gezondheid-en-milieu/duurzaamheids-beleid

[6] https://nl.wikipedia.org/wiki/Kalk#:~:text=In%20Nederland%20werd%20tot%202018,Groeve%20't%20Rooth%20de%20grootste.

relatively large beet sugar industry. Cosun (formerly known as Suiker Unie) is a large company with various branches that process the beet sugar harvest in a few months of every year. Calcium is used to remove various organic non-sugars from the raw juice when sugar is produced from sugar beet. The residual matter, a mix of carbonate of ***lime*** and organic residuals from the sugar beet, is returned to the beet growers under the name Betacal (Cosun)[7]. The growers spread Betacal on their fields to maintain the pH balance and improve the soil structure. As Sibalco is a non-ETS firm and Cosun is primary part of the food industry, renewable energy measures have not been discussed in further detail.

Cement

After 91 years, ENCI Maastricht stopped in 2018 the mining of marl for the production of Portland clinker. Since that time, the company has only been active in grinding and mixing components and supplying them to customers. But production costs rose too high, partly due to transport and storage, which prompted the parent company Heidelberg Cement to stop the latter activity as well in 2020. Only ENCI Rotterdam and Ijmuiden are open, using imported clinker, combined with blast furnace slag from Tata Steel.

Energy saving

The use of blast furnace slag and fly ash reduces the share of Portland clinker in the cement, which is the most energy intensive raw material. In 2017, ENCI IJmuiden has applied energy saving measures, like use of hot waste air for drying wet slag, saving natural gas, and automation of the dry grinding process.

Renewable energy

The former ENCI Maastricht plant used biomass, such as sewage sludge as biomass feedstock in its cement kiln. In 2017 the share of biomass was 27.1%[8]. In 2018, almost 90 percent of the sludge from sewage treatment plants was combusted. This mainly takes place in special sludge combustion plants, but also in cement kilns and power plants[9]. The Rotterdam plant has performed an inventory for placement of a wind turbine and solar panels[10]. A 0.995 MW solar PV installation is planned at the Rotterdam location.

Conclusion

The cement industry is very energy intensive, making energy savings by change of the raw material composition, for instance reducing the share of Portland clinker, highly relevant. Cement kilns are suitable for co-combustion of low-quality biomass such as sewage sludge. Like in any industry, solar panels can be placed and installation of nearby windmills may be possible in some cases.

[7] https://www.cosunbeetcompany.com/products/betacal
[8] ENCI sustainability update 2018
[9] https://www.clo.nl/indicatoren/nl0154-afzet-van-zuiveringsslib-naar-bestemming#:~:text=Steeds%20meer%20zuiveringsslib%20verbrand&text=In%202018%20wordt%20bijna%2090,regelgeving%20(VROM%2C%201997).
[10] https://www.enci.nl/nl/system/files_force/assets/document/18/a5/enci_rotterdam_ijmuiden_facts_and_figures_2017.pdf?download=1 (p5)

4 Chemicals & Fertilizers

Chemicals

Table 5 shows that the companies active in the manufacture of "other chemicals" together emit 9.3 Mton of CO_2-equivalent. The three largest firms are Chemelot (Sittard Geleen), Shell Nederland (Moerdijk) and Dow Benelux B.V. (Hoek) together responsible for 83% of these emissions (7.7 Mton). Their current and future renewable energy use has been investigated.

Table 4: Overview of companies active in the "other chemicals" industry in the Netherlands

Company	Location	ClassDescription	GHG emisison 2020
Albemarle Catalysts Company B.V.	Amsterdam	other chemical products n.e.c.	57,019
Alco Energy Rotterdam BV	Rotterdam	other organic basic chemicals	311,689
Biopetrol Rotterdam B.V.	Rotterdam-Botlek	soap and detergents, cleaning and polishing preparations	32,766
Cabot Norit Activated Carbon, Klazienaveen plant	Klazienaveen	other chemical products n.e.c.	61,450
Caldic Chemie B.V.	Europoort R-dam	other organic basic chemicals	12,628
Chemelot BKG 01, 02, 09, 10 and 11	Sittard-Geleen	other organic basic chemicals	2,723,976
Chemours Netherlands B.V.	Dordrecht	other organic basic chemicals	56,495
Croda Nederland B.V.	Gouda	other organic basic chemicals	28,881
Dow Benelux B.V. BKG 1, 2, 3, 5, 6, 7 and 9	Hoek	other organic basic chemicals	2,370,971
Emerald Kalama Chemical B.V.	Botlek-Rotterdam	other organic basic chemicals	80,798
ExxonMobil Chemical Holland B.V. (RAP, ROP and RPP)	Botlek Rotterdam	other organic basic chemicals	179,968
FUJIFILM Manufacturing Europe B.V.	TILBURG	other chemical products n.e.c.	22,716
Hexion B.V. BKG 1 and 2	Vondelingenplaat – Rotterdam	other organic basic chemicals	32,761
Indorama Ventures Europe B.V.	Europoort - Rotterdam	other chemical products n.e.c.	178,056
Johnson Matthey B.V.	MAASTRICHT	paints, varnishes and similar coatings, printing ink and mastics	2,700
Lyondell Chemie Nederland B.V. - Botlek, Europoort and Maasvlakte locatie	Rotterdam	other organic basic chemicals	282,524
PURAC Biochem B.V.*	GORINCHEM	other organic basic chemicals	23,850
Shell Nederland Chemie B.V., vest. Moerdijk BKG 1-8	MOERDIJK	other organic basic chemicals	2,579,901
Shell Nederland Chemie B.V., vestiging Pernis	Hoogvliet-Rotterdam	other organic basic chemicals	30,893
Shin-Etsu PVC B.V., locatie Botlek	Rotterdam	other organic basic chemicals	102,509
Sonac Burgum B.V.	SUMAR	other chemical products n.e.c.	37,463
Sonac Vuren B.V.	VUREN	glues	27,801
Sonneborn Refined Products	AMSTERDAM	other chemical products n.e.c.	1,3871
Total			**9,251,686**

* This is case study partner Corbion.

Source: list of EU ETS companies

Chemelot, Sittard-Geleen

Chemelot is a cluster of chemical industries located at the Chemelot site in Limburg. The Cluster Energy Strategy Chemelot 2030 – 2050 (CES)[11] provides insight into the demand and availability of infrastructure for the industry cluster. Next to Chemelot, the strategy is linked up with the Limburg Energy Agreement (LEA).

Electrification plays a major role in the sustainability plans of Chemelot and the LEA companies. This partly concerns existing techniques such as electric boilers and the replacement of steam turbines by electric drives. This partly concerns new techniques that need to be further developed and scaled up technologically and economically, such as the electrification of ovens and furnaces and plasma technology. The possible electrification of the cracking furnaces requires special attention because of the major impact.

Hydrogen already plays a substantial role as a raw material in the chemical industry including the Chemelot site. It is an important building block for the production of ammonia, but also as a raw material for, among other things, synthetic fibres. The hydrogen production amounts to approximately 200 kt per year and is at the moment produced from natural gas. To make Chemelot more sustainable before 2030, part of the resulting process CO_2 can be captured and stored in depleted gas fields in the North Sea. According to the HyWay27 project[12], from 2027 onwards Chemelot could be connected to the hydrogen backbone of the Gasunie with connections to other industry clusters. Existing natural gas pipelines are hereby made suitable for the transport of hydrogen and missing parts of the route.

In concrete terms, the CES advocates:

- An accelerated plan study into and decision on extending the 380 kV grid from Maasbracht towards Graetheide. The need for a 380 kV grid near Chemelot is not only due to the increasing electricity demand at Chemelot, but also to the expected electricity demand in South Limburg as a whole.
- Support in the further elaboration and realization of a pipeline corridor for product pipelines and the transport of hydrogen and CO_2 from Rotterdam via Chemelot to North Rhine-Westphalia (NRW).
- Connection to a (public, regulated) hydrogen infrastructure to and from Chemelot and, where possible, the other industries within the cluster for the supply of sustainable hydrogen.

Chemelot is an interesting example of a cluster of companies that collaborate with the regional authorities advocating a new energy infrastructure to make their future energy infrastructure carbon neutral.

Shell Nederland Chemie B.V, Moerdijk

Shell Moerdijk processes naphta, gasoline and LPG from refineries into base chemicals for the plastics industry, like monomers. The processing capacity is about 4.5 Mton/year. It has three main factories: Moerdijk Lower Olefins (MLO), Moerdijk Ethene Oxide and Derivates (MEOD) and

[11] See https://www.chemelot.nl/duurzaamheid/cluster-energie-strategie-chemelot-2030-2050
[12] https://www.hyway27.nl/actueel/hyway-27-realisatie-van-het-landelijk-waterstofnetwerk

Moerdijk Styrene monomer and Propene Oxide (MSPO)[13]. Shell modernises the 16 oldest furnaces of its cracker at MLO[14], replacing them with 8 more efficient and cleaner furnaces. One large steam compressor is now driven by electricity. Moreover, in 2018 a 27 MWe solar park has been installed at the premises of Shell Moerdijk[15]. Shell Moerdijk is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) initiated by PBL and TNO. The project aims to support industry, policymakers, analysts and the energy sector in their common efforts to achieve deep decarbonisation[16]. Decarbonisation options for Shell Moerdijk include heat integrated distillation columns and heat pumps, heat recovery, process control, coalesce-filtration units, membranes (for gas separation), adsorption heat pumps, electrification, hydrogen as fuel, biomass to bio-ethylene process, methanol to olefin process, carbon capture and storage or utilisation (PBL 2020)[17].

Dow Benelux B.V., Hoek, Terneuzen

In June 2021, Dow Benelux outlined its roadmap to reduce current CO_2 emissions from its Terneuzen, the Netherlands, operations by more than 40 percent by 2030 on its path to achieve net CO_2 neutrality by 2050. The roadmap to CO_2 neutrality is designed in three phases[18].

- In the first phase, the plan foresees the construction of a clean ***hydrogen plant*** where by-products from core production processes would be converted into hydrogen and CO_2. The hydrogen would be used as a clean fuel in the production process. The CO_2 would be captured and stored until alternative technologies develop, and Dow will also look for ways to enable usage of the CO_2 in its processes rather than storing it. The hydrogen plant is expected to startup in 2026 and would allow Dow in Terneuzen to reduce CO_2 emissions by approximately 1.4 million tons per year.
- In the second phase, by 2030, Dow will ***capture CO_2*** from its ethylene oxide plant and replace some gas turbines with electrical motor drives. This will avoid a further 300,000 tons of CO_2 emissions per year.
- The third and final phase of the plan will develop and implement additional breakthrough technologies to replace fuel usage in the production processes. An example is Dow's previously announced collaboration with Shell to ***electrify*** ethylene steam cracking furnaces. These furnaces currently rely on fuel combustion, which makes them CO_2-emission intensive when not fired on clean hydrogen. Switching to electrical cracking with clean electricity will reduce the CO_2 footprint of the production process to near zero emissions.

Except the press articles and website, no details of this multigeneration plan could be found.

[13] https://nl.wikipedia.org/wiki/Shell_Moerdijk
[14] https://www.duurzaam-ondernemen.nl/shell-moerdijk-neemt-forse-stap-in-energietransitie-met-nieuwe-fornuizen/
[15] https://nl.wikipedia.org/wiki/Shell_Moerdijk
[16] https://www.pbl.nl/en/publications/decarbonisation-options-for-large-volume-organic-chemicals-production-shell-moerdijk
[17] https://www.pbl.nl/sites/default/files/downloads/pbl-2020-decarbonisation-options-for-large-volume-organic-chemicals-production-shell-moerdijk_3483.pdf
[18] https://nl.dow.com/nl-nl/news/dow-benelux-presents-step-by-step-plan-to-support-the-dutch-climate-agreement-achieve-co2-emission-neutrality.html



Fertilizers

Table 5 shows that three fertilizer companies together produce 5.1 Mton of CO_2-equivalent. Yara Sluiskil is the largest firm, responsible for 3.3 Mton (65%) of these emissions, followed by Chemelot with 1.8 Mton (35%) and Rosier Nederland with 0.02 Mton (0.3%).

Table 5: Overview of companies active in the fertilizer industry in the Netherlands

Company	Location	ClassDescription	Carbon emission in 2020
Chemelot BKG 03 – 07	Sittard	Fertilisers and nitrogen compounds	1,754,172
Rosier Nederland B.V.	Sas van Gent	Fertilisers and nitrogen compounds	17,663
Yara Sluiskil B.V. BKG 1 - 6	Sluiskil	Fertilisers and nitrogen compounds	3,297,569
Total			**5,069,404**

Source: list of EU ETS companies

Chemelot (OCI Nitrogen)

OCI Nitrogen is a nitrogen fertilizer and melamine producer comprised of nine interconnected plants located on a fully integrated production site at Chemelot in Geleen. In its sustainability strategy, OCI seeks to decarbonise its production processes through: blue hydrogen (CCUS), circular hydrogen (Waste-to-Syngas), green hydrogen (Renewable Electrolysis) and bio-based feedstock (2nd & 3rd generation)[19]. The supply of low carbon hydrogen is crucial in OCI Nitrogen's decarbonisation strategy. OCI Nitrogen is one of the organizations that joined the Netherlands Hydrogen Coalition[20], which aims to encourage the Dutch government to stimulate green hydrogen for further sustainability of the energy supply. As already mentioned in the paragraph on chemicals, in its Cluster Energy Strategy, Chemelots investigates the possibilities for hydrogen infrastructure. Moreover, OCI Nitrogen sees a relevant role for itself in decarbonisation of the economy as supplier of green ammonia as shipping fuel. In May 2019, OCI Nitrogen became the first producer in Europe to use bio-methane to produce and sell green ammonia. The sustainable product and mass balance system is ISCC+ certified and enables customers to produce more sustainable downstream products[21].

Yara Sluiskil

The Climate Roadmap 2030[22] of Yara Sluiskil defines three tracks: (1) adjustment and replacement of existing installations with low carbon emission installations, (2) carbon capture and storage and (3) green hydrogen. Like OCI Nitrogen, Yara is part of the Netherlands Hydrogen Coalition. Yara points at Adblue as important ammonia product reducing NOx emissions, and sees new opportunities of green ammonia as shipping fuel. They also point to the use of digital tools like the GrassN app for efficient use of fertiliser.

[19] https://www.oci.nl/media/1902/oci-2020-annual-report.pdf
[20] https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/nieuws/Waterstofcoalitie%20-%20Waterstofpact.pdf
[21] https://www.oci.nl/our-stories/working-towards-europes-emissions-targets/
[22] https://www.yara.nl/contentassets/6ca92ab7997f4f3faa50fd9ada6d6855/2210781-duurzaamheidsverslagsite.pdf/

Conclusion
The Dutch chemical and fertiliser industries are particularly dependent on green hydrogen in order to decarbonise their production processes. If green hydrogen would be available, it could change these industries in suppliers of green fuels and processes, like for instance green ammonia as shipping fuel.

5 Steel

Table 6 gives an overview of EU-ETS companies active in the steel industry in the Netherlands. Tata Steel IJmuiden is a large steel company with a carbon emission of 5.8 Mton in 2020. FN Steel is a relatively small player specialised in steel wires. They have an emission of 17.5 ktonnes, 0.3% of the emission of Tata Steel. Therefore, we will further focus on Tata Steel.

Table 6: Overview of companies active in the steel industry in the Netherlands

Company	Location	ClassDescription	EU ETS CO_2 emission in 2020 (tCO_2)
Tata Steel IJmuiden bv BKG 1	Velsen-Noord (gem. Velsen	Manufacture of basic iron and steel and of ferro-alloys	5,711,530
Tata Steel IJmuiden bv BKG 2	Velsen-Noord (gem. Velsen)	Manufacture of basic iron and steel and of ferro-alloys	74,642
FNsteel B.V.	Alblasserdam	Manufacture of basic iron and steel and of ferro-alloys	17,479

Source: list of EU ETS companies

Tata Steel Netherlands (TSN)
The Tata Steel Sustainability Report 2019-2020 (Tata 2020)[23] provides insight in the plans Tata has to reduce CO_2 emissions substantially in the coming years. Tata Steel's ambition is to produce steel without CO_2 emissions by 2050 through investing in a mix of breakthrough technologies, such as carbon capture, utilisation and storage (CCUS), HIsarna and the use of hydrogen.

CCUS
Tata Steel plans to build a plant which captures the carbon dioxide we currently emit. They recently started the first phase of the "Everest project" to capture CO_2 from the blast furnaces in the relatively short term, and to transport it to former gas fields under the North Sea for storage. In the second phase, Tata will use blast furnace emissions for conversion into sustainable raw materials for the chemical industry and synthetic fuels. This project will be an important step towards CO_2 reductions by 2030. Another project "Athos" will look at carbon usage in the Amsterdam region, using existing infrastructure as much as possible.

HIsarna

[23] Tata (2020)Tata Steel in Europe Sustainability Report 2019/2020
https://www.tatasteeleurope.com/sites/default/files/TSE%20Sustainability%20report%202019-20%20(EN).pdf

HIsarna, is Tata's innovative iron-making technology, wherein the pre-processing of ores and coal into sinter and pellets can be skipped. Its concentrated CO_2 off-gas is ideally suited to carbon capture and storage (CCS). It has many other unique benefits, such as eliminating the emissions of other pollutants such as nitrogen oxides and sulphur dioxide from the processes it replaces. Moreover, it can be a gamechanger as we move towards a more circular economy. In combination with an Electric Arc Furnace, it is also possible to recover zinc - often found in scrap - for reuse. By 2033, Tata's ambition is to have it scaled up it at full scale and it is ready to replace one of their blast furnaces. HIsarna can cut up to 100% of CO2 emissions, when combined with carbon capture.

Hydrogen
Together with partners, TSN is working to introduce hydrogen as a fuel source to help creating a hydrogen infrastructure. Producing hydrogen in large enough quantities is a challenge, but if this would succeed, Direct Reduced Iron (DRI) technology could be applied as alternative iron production method. In its Tata Steel Sustainability Report 2019-2020 Tata estimates this could be the case in 15 – 25 years from now. However, recent developments indicate faster implementation.

Update 2021
On the 15th of September 2021, Tata Steel Netherlands (TSN) decided to skip the CCU option and go for accelerated introduction of hydrogen-based steel making, via Direct Reduced Iron (DRI). Roland Berger (2021)[24] conducted a feasibility study "climate neutral pathways TSN IJmuiden", stating that TSN will transform its site in three steps: successively replacing two blast furnaces, and ultimately operating entirely on hydrogen. TSN will have to make substantial investments to realize the new DRI installations and electric ovens. This report also emphasizes that the preconditions for the realization of the first DRI installation before 2030 lie in three areas: (1) supporting infrastructure for green electricity, hydrogen and initially natural gas, (2) market conditions for the cost-effective availability of sufficient quantities of green hydrogen, green electricity, and natural gas, and (3) government support in four areas. The report states that government support is needed in the form of appropriate support mechanisms, facilitating rapid licensing, amending legislation and regulations for the realization of the energy transition and stimulating the hydrogen market and infrastructure. The Dutch government works on measures to support large industries like TSN as further described in chapter 7. Recent interactions of the Dutch government with TSN are described in the letter from the Ministry of Economic affairs to the Parliament of 1 December 2021[25] as the parliament had adopted several motions regarding the sustainability of TSN.

Tata Steel participates in the Windpark Ferrum, located at Tata's premises in IJmuiden near the North Sea coast. It consists of three turbines with a total capacity of 7 MW. Near and at the sites of Tata steels some solar PV projects are planned and realised. In the future Tata will be connected to wind parks located in the North Sea.

24 https://energeia-binary-external-prod.imgix.net/C01vDuVLmU1muqCfkMrG7hd1_oE.pdf?dl=Roland+Berger+%7C+Haalbaarheidsstudie+klimaatneutrale+paden+TSN+IJmuiden.pdf

25 https://www.rijksoverheid.nl/documenten/kamerstukken/2021/12/01/kamerbrief-over-verduurzaming-tata-steel-nederland

Conclusion

Direct Reduced Iron (DRI) technology using green hydrogen will play a key role in the decarbonisation of the Dutch steel industry, which is dominated by Tata Steel Netherlands, on the condition that sufficient green hydrogen will be made available in the coming years, depending on expansion of wind parks at sea.

6 Ceramics & Glass

Ceramics

Table 7 shows that 17 locations of ceramics producers fall under EU-ETS, together producing 188 ktonnes of carbon emissions in 2020. The sector is rather stable and not many locations (that fall under EU-ETS) have been closed since 2005.

Table 7: Overview of companies active in the ceramics industry in the Netherlands

Company	Location	ClassDescription	Carbon emission in 2020
Koninklijke Mosa B.V., locatie Vloertegel	Maastricht	Manufacture of ceramic tiles and flags	11,079
Koninklijke Mosa BV, locatie Wandtegel	Maastricht	Manufacture of ceramic tiles and flags	18,683
Wienerberger Dakpannenfabriek Janssen Dings	Tegelen	Manufacture of bricks, tiles and construction products, in baked clay	10,739
Wienerberger Dakpannenfabriek Narvik Tegelen	Tegelen	Manufacture of bricks, tiles and construction products, in baked clay	8,854
Wienerberger Dakpannenfabriek Narvik Deest	Deest	Manufacture of bricks, tiles and construction products, in baked clay	7,300
Monier Tegelen	Tegelen	Manufacture of bricks, tiles and construction products, in baked clay	11,801
Monier Woerden	Woerden	Manufacture of bricks, tiles and construction products, in baked clay	14,210
Kleiwarenfabriek Facade Beek	Beek	Manufacture of bricks, tiles and construction products, in baked clay	8,602
B.V. Steenfabriek Hedikhuizen	HEDIKHUIZEN	Manufacture of bricks, tiles and construction products, in baked clay	15,829
B.V. Steenfabriek Huissenswaard	ANGEREN	Manufacture of bricks, tiles and construction products, in baked clay	22,694
Wienerberger B.V. Steenfabriek Heteren	Heteren	Manufacture of bricks, tiles and construction products, in baked clay	8,552
Wienerberger B.V. Steenfabriek Kijfwaard Oost	Pannerden	Manufacture of bricks, tiles and construction products, in baked clay	12,775
Wienerberger B.V. Steenfabriek Thorn	Thorn	Manufacture of bricks, tiles and construction products, in baked clay	12,807
Wienerberger B.V. Steenfabriek Wolfswaard	Opheusden	Manufacture of bricks, tiles and construction	14,349

		products, in baked clay	
Steenfabriek Linssen BV	KERKRADE	Manufacture of bricks, tiles and construction products, in baked clay	3,111
Steenindustrie Strating B.V.	OUDE PEKELA	Manufacture of bricks, tiles and construction products, in baked clay	5,436
Wormdal Vastgoed BV	EYGELSHOVEN	Manufacture of bricks, tiles and construction products, in baked clay	1,009

Source: list of EU ETS companies

Vereniging Koninklijke Nederlandse Bouwkeramiek, the Dutch branch organisation of the ceramics industry has developed a *Building Ceramics Technology Roadmap 2030*[26], which defines four lines of action: (1) sustainable manufacturing, (2) product innovation and innovation of production process, (3) strengthening circularity and (4) sustainable use of raw materials. Within sustainable manufacturing, renewable sources are mentioned as third option, after energy reduction in the firing process and in the drying process. Renewable energy options like electrification, biofuels, hydrogen and the combination of hydrogen and hydrogen will be investigated, according to the roadmap.

Wienenberger B.V. (with 7 EU-ETS locations in the Netherlands) states in their 2020 sustainability report[27] that they will reduce their scope 1 emissions by developing new technologies to enhance energy efficiency in the drying and firing process, avoid or recover waste heat, and optimise processes and products. Secondly, the purchase of renewable electricity will substantially reduce the scope 1 emissions (market based). According to the sustainability report (p48), so far, the use of renewable energy used in their production processes has been negligible. Natural gas comprises 85% of their energy consumption followed by electricity (14%).

Glass

Table 8 shows that 7 locations of glass producers fall under EU-ETS, that together emitted 422 ktonnes of CO_2-equivalents in 2020. Since 2015 the glass industry has reduced emissions by 22%.

Table 8: Overview of companies active in the glass industry in the Netherlands

Company	Location	Class Description	Carbon emission in 2020
O-I Manufacturing Netherlands B.V., vestiging Leerdam	Leerdam	Manufacture of hollow glass	87,949
O-I Manufacturing Netherlands B.V., vestiging Maastricht	Maastricht	Manufacture of hollow glass	89,402
Ardagh Glass Moerdijk B.V.	Moerdijk	Manufacture of hollow glass	54,277
PPG Industries Fiber Glass BV	Westerbroek	Manufacture of glass fibres	39,330

[26] https://www.knb-keramiek.nl/media/268879/knb_building-ceramics-technology-roadmap-2030.pdf
[27] https://www.wienerberger.com/content/dam/corp/corporate-website/downloads/sustainability/2020/2020-Wienerberger-Sustainability-Report_EN.pdf

Ardagh Glass Dongen B.V.	Dongen	Manufacture of hollow glass	88,762
Saint-Gobain Construction Products Nederland B.V.	Etten-Leur	Manufacture of glass fibres	47,792
Owens Corning Veil Netherlands B.V.	Apeldoorn	Manufacture of glass fibres	14,522

Source: list of EU ETS companies

O-I Manufacturing Netherlands is part of the similar named large multinational, which is part of the Science-Based Target Initiative. According to the O-I Sustainability report 2021[28], their (global) goal is to reach a 25% reduction in GHG emissions by 2030 with an interim target of 10% by 2025. To achieve these goals, they are looking to increase the percentage of renewable energy consumed at their facilities, explore alternative fuels, develop innovations in their manufacturing processes and products, increase energy efficiency in their plants, increase the use of recycled content in their containers, and encourage post-consumer recycling of glass. Besides buying renewable electricity certificates, and the possibility to use biofuels and other alternative fuels in their innovative MAGMA glass production technology, no concrete renewable energy projects are mentioned in the O-I sustainability report.

According to the sustainability report of Ardagh Glass, they would like to reduce their scope 2 emissions to zero by 2030 with a combination of on-site, near-site and off-site renewable electricity projects across their European and American facilities. They are investigating renewable thermal solutions to reduce their scope 1 CO_2 emissions through electricity of thermal loads and fuel switching to low or no carbon fuels.

Conclusion
Sustainability strategies within the ceramic and glass industry mainly focuses on circularity aspects and energy efficiency measures, while renewable energy plays a less prominent role, often limited to reduction of scope 2 emissions by buying renewable electricity certificates.

7 Challenges and potential measures

Synthesis
The previous chapters gave a snapshot of the plans of selected Dutch industrial sectors to decarbonise. Table 9 shows the main solutions considered and or/applied by the largest companies within each sector.

Table 9: Overview of renewable energy solutions and other decarbonisation options as described by prominent Dutch companies of the selected industrial sectors.

Industrial sector	Renewable energy solutions	Other decarbonisation options
Non-ferrous metals	Solar, wind, power net balancing	Optimal recycling

[28] https://www.o-i.com/wp-content/uploads/2021/12/O-I_SustainabilityReport_2021.pdf

(aluminium)		
Lime & cement	Sewage sludge combustion, other biomass, wind, solar	Reducing share of Portland clinker in cement by using blast furnace slag and fly ash
Chemicals & fertilisers	Electrification of production processes, hydrogen	Carbon capture and utilisation, greening other sectors (e.g. ammonia-based fuels for shipping)
Steel	Hydrogen, wind	Carbon capture utilisation and storage, innovative technologies (HIsarna)
Ceramics and glass	Renewable electricity certificates	Energy efficient drying and firing processes, increased recycled content

Source: own compilation

Virtually all companies report about their strategies to decarbonize by 2030 and often underline the aim of the Dutch Climate Agreement to become completely carbon neutral by 2050. Some companies limit their current effort to mentioning some possible measures without a detailed plan, while in other cases an extensive strategy has been formulated. The Cluster Energy Strategy Chemelot 2030 – 2050 is a good example how a cluster of chemical industries actively seek cooperation in the establishment of a hydrogen infrastructure in the Netherlands, working together with the Regional Energy Strategy and national level initiatives.

Challenges

Hydrogen and electrification play a major role in the decarbonisation plans of the Dutch industry. Both options depend strongly on the availability of large volumes of renewable electricity. At the premises of these industries, the possibilities of renewable electricity production are of course limited. Nevertheless, at several locations, solar parks and some wind turbines have been realised.

Achieving the goals of the Climate Agreement and the further transition to an emission-free economy in 2050 require a significant expansion of the energy infrastructure. Realizing this in a timely manner is complicated. Industrial companies, network operators, energy producers and regional governments have jointly drawn up Cluster Energy Strategies (CESs) in 2021, covering five areas, while the sixth related various smaller industrial areas will be developed soon.

Growing electricity demand and long realization time make upgrading electricity grids urgent. When all plans would be implemented, the electricity demand of the industry will increase from **43 TWh now to 128 TWh in 2030**[29]. About 40 percent of that growth is due to the production of hydrogen via electrolysis. The electrolyser capacity in the CESs adds up to about 9 GW in 2030. The extra electricity demand requires a proportional increase in CO_2-free power to prevent growing carbon emissions in the electricity sector. Priorities will have to be set in the construction of electricity

[29] https://www.pbl.nl/publicaties/reflectie-op-cluster-energiestrategieen-ces-1-0



Figure 2: Overview of Cluster Energy Strategies (CES) in the Netherlands. The sixth CES consists of several smaller industrial areas as indicated on the map in orange/brown.

infrastructure.

Potential measures

The main solution is to accelerate renewable energy generation and to develop the infrastructure to bring the green electricity and hydrogen to the industries. The renewable electricity capacity planned to be produced on land, is elaborated in the 30 Regional Energy Strategies (RES). The RES strategies are expected to result in 35 TWh/year renewable electricity production by 2030. However, most renewable electricity will have to be produced by wind parks at sea. According to the Climate Agreement[30] wind parks at sea with a joint capacity of 11 GW will produce 49 TWh/year by 2030. Based on calculations made in the Noordzee Energy Outlook in 2020, it was decided to increase this capacity to 11.5 GW, ensuring that 49 TWh/year is really achieved in 2030[31]. Given that in 2021 the capacity of wind at sea reached 2.5 GW, expected to grow to 4.5 GW by 2030, a large effort still has to be made[32,33]. The 35 TWh renewable electricity on land plus 49 TWh wind at sea as foreseen in the Dutch Climate Agreement of 2019 add up to 84 TWh of renewable electricity. This amount is well below the 128 TWh needed by the industry according to the Cluster Energy Strategies. Therefore, the advisory board "Additional Effort"[34] indicated that 45 TWh/year additional renewable electricity should be available by 2030, meaning that about 10 GW extra capacity of wind at sea should be realised, plus additional infrastructure to bring the electricity (or hydrogen if already converted at sea) to the (mainly industrial) users. This additional capacity is still under discussion (by Feb 2022).

In order to solve bottlenecks that could lead to delays in the roll out of renewable energy infrastructure, the national government has set up the National Infrastructure Program for Sustainable Industry (**PIDI**)[35]. In this programme, all parties involved work together to accelerate the realization of the required infrastructure. As a first step, Cluster Energy Strategies are developed

30 https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord
31 https://zoek.officielebekendmakingen.nl/kst-32813-646.html
32 https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee
33 https://windopzee.nl/onderwerpen/wind-zee/wanneer-hoeveel/wind-zee-2030/
34 https://zoek.officielebekendmakingen.nl/blg-979271
35 https://www.rijksoverheid.nl/documenten/publicaties/2021/05/20/programma-infrastructuur-duurzame-industrie-plan-van-aanpak

indicating the demand for electricity, hydrogen, and removal of CO_2. The plans and projects described in the CES are input to the multi-year programme infrastructure energy and climate **MIEK**[36]**,** a programme supporting energy and raw materials infrastructure projects of national importance that contribute to climate transition and stimulate the earning capacity of the Netherlands. For accelerated realization of the infrastructure, PIDI also aims to support the clusters in permit procedures and planning procedures and makes proposals for removing financial and organizational bottlenecks. In addition, legislation and regulations will have to be amended to enable proactive and planned investments in infrastructure by network operators.

As described above, the challenge to increase the supply of renewable hydrogen and electricity for the Dutch industry including the required infrastructure is being addressed in national programmes and regional strategies. The question remains whether all capacity and infrastructure will be realised by 2030, a period of only eight years.

[36] In Dutch: Meerjarenprogramma Infrastructuur Energie en Klimaat



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RE4INDUSTRY

100% Renewable Energies

for Energy Intensive Industries

Grant Agreement Nº 952936

D3.1 - Ells Sector Status in Europe

Country Report – Spain

Author: Clara Jarauta

Lead Beneficiary: CIRCE

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Abbreviations

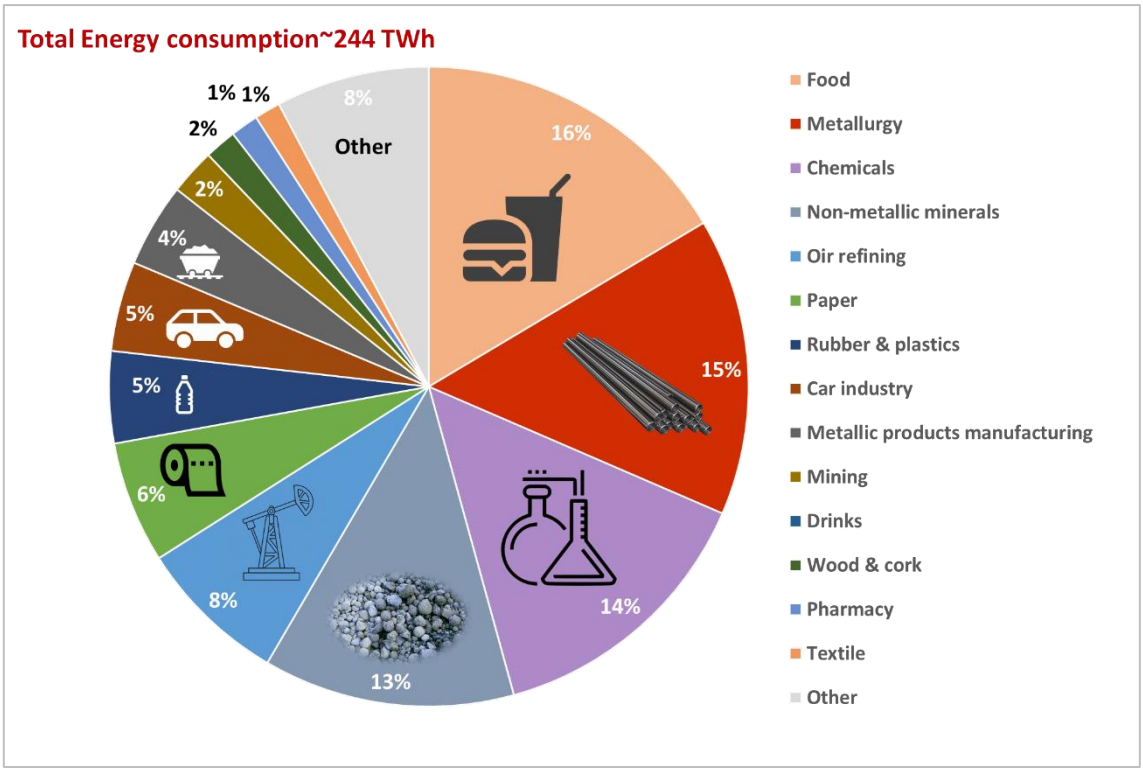
Abbreviation	Definition
EIIs	Energy Intensive Industries
INE	Spanish National Statistics Institute
CNAE	National Classification of Economic Activities
GHG	Green House Gases
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage and Usage
REs	Renewable Energies
SCU	Smart Carbon Usage
CDA	Carbon Direct Avoidance
PPAs	Power Purchase Agreements
RDL	Royal Decrete Law



1 Introduction

The present report aims to provide an overview of the Energy Intensive Industries (EIIs) sector in Spain. The EII sector is one of the most important industrial activities in Spain. According to the Spanish National Statistics Institute (INE)[1], it accounts around the 60% of the total energy consumption in Spain, some of them being very relevant, such as chemical, iron & steel, non-ferrous metals or paper sectors, among others.

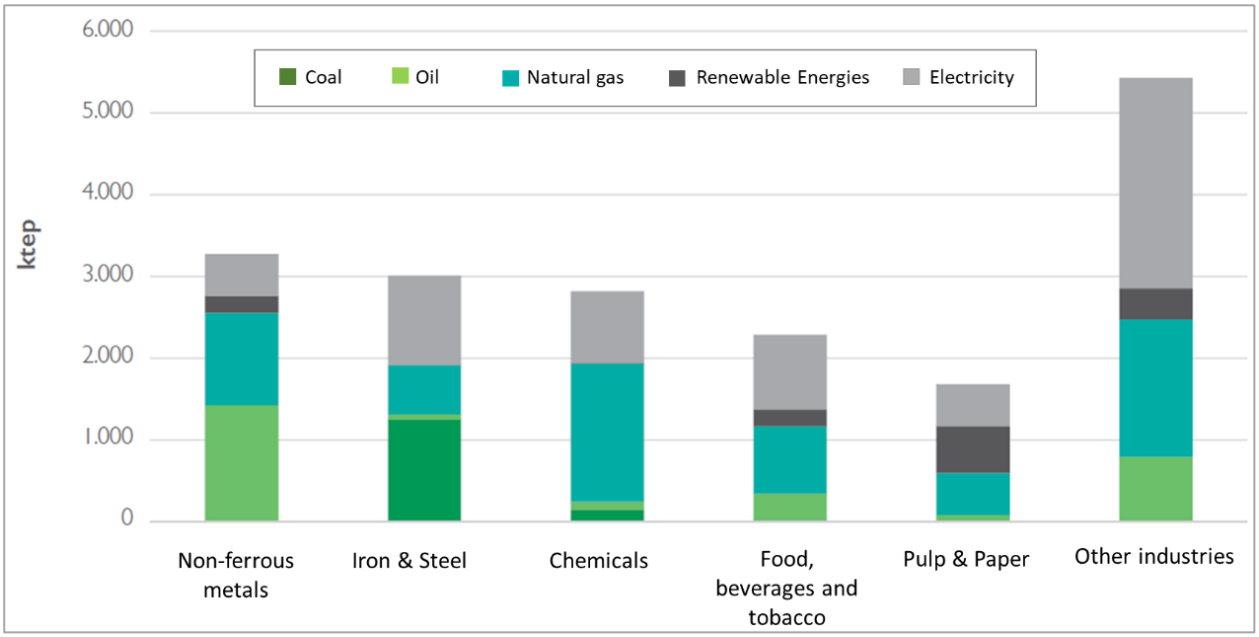
Figure 1. Energy consumption by sector. Source: INE



Almost all the energy required for the intensive processes is provided by non-renewable sources, such as coal, oil and natural gas. Electricity plays a key role as well, but renewable energies have a minor presence in the industrial energy landscape.

[1] Spanish National Statistics Institute. Available on: https://www.ine.es/

Figure 2. Energy consumption in EII sector – Spain (ktep). Source: MITECO [2]



Some characteristics of energy-intensive industry make it difficult to decarbonize the sector. For example, primary production process equipment for primary production processes is characterized by high initial investment costs and is designed with a very long service life, e.g., up to 50 years in the case of cement plants [3].

The industry has made numerous efforts in the past, mainly due to its own need to maintain its economic competitiveness (and thus reduce the energy and CO_2 costs associated with its activity). However, due to the characteristics of the sector, it still accounts for 23.5% of national energy consumption [3].

In the following sections, the major features of the EII sectors investigated in the RE4Industry project as applicable to Spain are described: active companies, energy consumption profile and major activities related to renewable energy utilization. The main challenges and potential measures faced by the EII sector in Spain are presented in a concluding chapter.

2 Chemical sector

The chemical sector is key in the economic landscape in Spain. It covers more than 3,000 companies

[2] MITECO (Spanish Ministry for the Ecological Transition and Demographic Challenge). Available on: https://www.miteco.gob.es/es/
[3] Borrador Estrategia de descarbonización a Largo Plazo 2050. Spanish Ministry for the Ecologic Transition and Demographic Challenge. Available on: https://energia.gob.es/_layouts/15/HttpHandlerParticipacionPublicaAnexos.ashx?k=16824

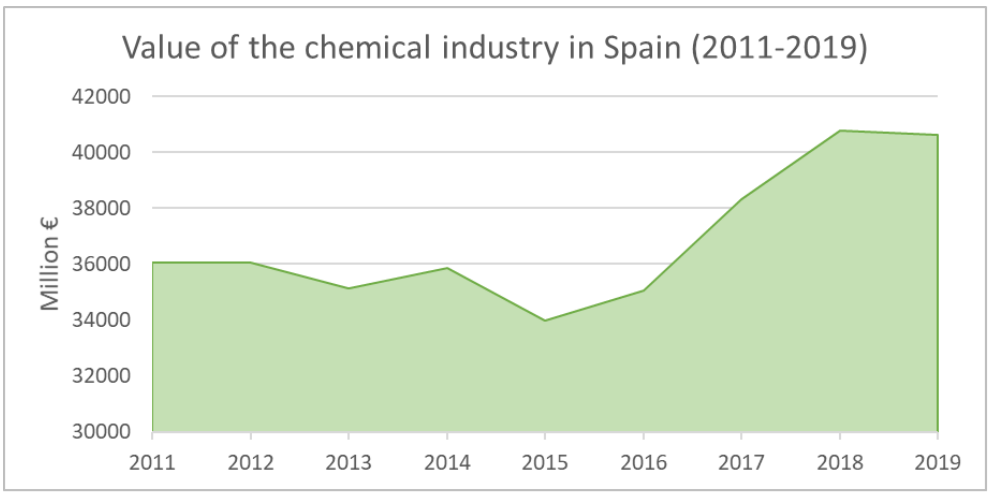
and is one of the largest and most consolidated industrial sectors in this country. Its weight as economic engine translates into the generation of 5.4% of GDP, more than 13% of industrial GDP. With a turnover of 77,241 million euros, of which almost 60% is invoiced in foreign markets (up to 44,527 million euros) and a growing weight in countries outside the European Union, the chemical sector is the second largest exporter of the Spanish economy, only behind the automobile industry [4].

This sector is quite complex in terms of the manufactured products. According to the Spanish CNAE-2009 classification (National Classification of Economic Activities), there are six main categories:

- Basic chemicals, nitrogen compounds, fertilisers, plastics and synthetic rubber in primary forms
- Pesticides and other agrochemicals
- Paints, varnishes, lacquers and similar coatings; printing inks and mastics
- Soap and detergents, cleaning and polishing preparations; manufacture of perfumes and cosmetics
- Artificial and synthetic fibres
- Other chemical products

The total value of the chemical industry has been increasing in the last decade, reaching its maximum values in 2018[5].

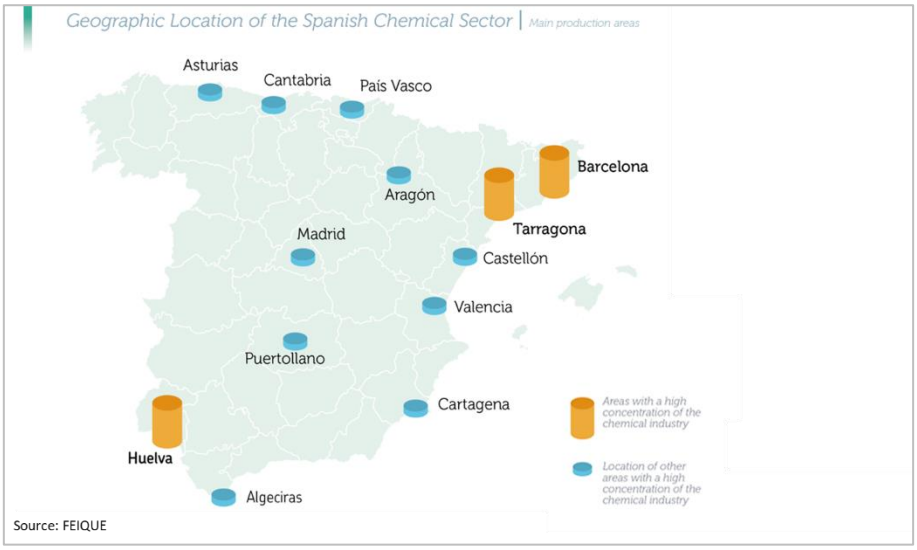
Figure 3. Chemical sector value in Spain [5]



[4] The sector in numbers. FEIQUE. Available on: https://www.feique.org/el-sector-en-cifras/
[5] Chemical industry in Spain: statistics. Available on: https://es.statista.com/temas/5428/la-industria-quimica-en-espana/#topicHeader__wrapper

Regarding the sector location, the largest activity volume is concentrated in Catalonia and Andalusia regions, but there are also smaller areas with high relevance for the sector.

Figure 4. Location of the chemical sector in Spain. Source: FEIQUE [6]



This intensive sector has always shown a special sensitivity to the aspects covered by what is today Corporate Social Responsibility and which, particularly in the sector, is embodied by the Responsible Care initiative. Thus, decarbonising this sector is also one of their main targets. For this purpose, a specific research platform was developed in order to kick off new R&D&I projects, called SusChemInnova [7].

It is one of the industrial sectors with the highest growth projections worldwide. The increase in production needed to meet the new international demand is estimated at 4.5% per year until 2030. In addition, Spain is one of the most preferred destinations for R&D&I projects in the chemical industry in Europe (41 countries) and ranks 4th in the number of new projects by multinationals (period 2003-2020, FDI markets data) [8].

3 Petrochemical sector

The petrochemical activities in Spain are situated near to the chemical industry. However, it is linked to the refinery plants in Spain. There are nine refineries in the peninsula that in 2019 processes

[6] Economic radiography of the Spanish chemical sector. Available on: https://www.feique.org/radiografia-economica-del-sector-quimico-espanol/

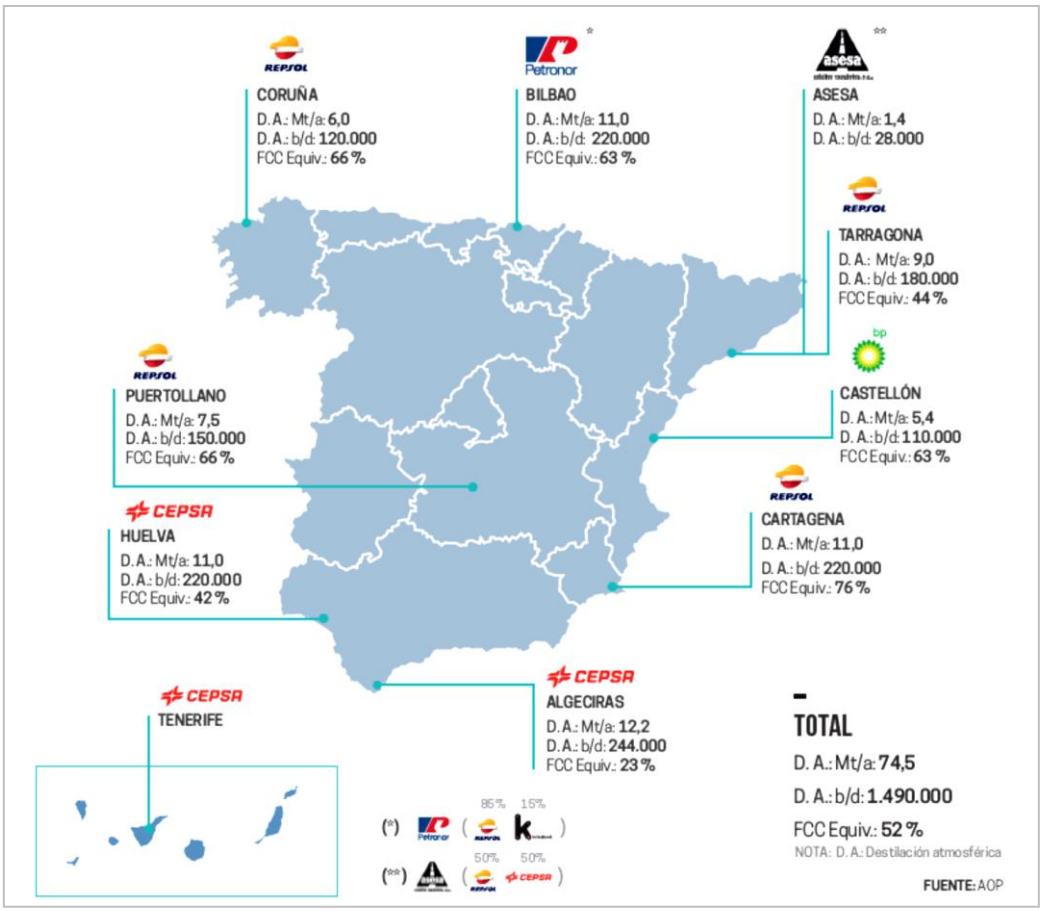
[7] SusChemInnova webpage. Available on: http://www.suschem-es.org/

[8] Chemical Industry, Invest in Spain. Spanish Ministry of Industry, Trade and Tourism. Available on: https://www.investinspain.org/es/sectores/industria-quimica

66.5 million of tons of crude oil and raw materials. The commercial balance of the refinery industry is positive, exporting 3.3 million of tons, although most of the production is for internal purposes. The main exported products were gasoil and petrochemical raw materials.

These refineries represent the 2.2% of the industrial GDP, the investment in 2019 was 957 M€, and the sectorial turnover is about 39,000 M€. It employs more than 200,000 people. The tax collection, regarding VAT and the special Hydrocarbon tax, reaches 19,800 M€. Therefore, it is a key strategic sector for the industrial development of the country [9].

Figure 5. Location of refineries in Spain [9]



4 Metallic sector

4.1 Ferrous metals: Iron and steel

'Steel' is the name given to alloys of iron (Fe) and carbon (C) in which the carbon content in solid solution in the iron is below 2.1%. Therefore, there is not just one type of steel but many different

[9] AOP, "Memoria 2019," 2019. Available on: https://www.aop.es/memorias/2020/07/17/memoria-2019/

steels. Both iron and carbon are found in high proportions in the earth's crust, making steel a highly available material. However, the high technology used in its manufacturing process makes steel a strategic material and many countries are not able to produce certain qualities.

According to UNESID (the Association of the Spanish Steel and First Transformation Steel Producing Companies), Spain accounts with 22 steel plants and there are 50 rolling and first transformation facilities. Most of the factories are located in the north of Spain, particularly Asturias and Basque Country regions, even though this sector is quite extended along the country. The iron & steel sector in Spain production is around 1.3 million tons per year with the use of about one million tons of recycled material. 10% of the total production was stainless steel, 75% was produced via the electric route and with most of the steel produced through hot rolling process [10].

Figure 6. Factories for steel production and transformation in Spain (2021). Source: UNESID[10]



Steel is manufactured and recycled through two routes that are complementary, since the first starts from iron ore and the second recycles the multiple steel waste at the end of its useful life, commonly called steel scrap. The first covers the increase in world steel consumption, and the second closes the material cycle with very high environmental, economic and social efficiency.

More than 500 million tons of steel are recycled every year in Spain, without any need to intervene in this cycle, except for fulfilling with the subsequent environmental controls and requirements. In this regard, Spain (together with other relevant steel producing countries) is at the head of the steel

[10] UNESID. Steel production. *Available on: https://unesid.org/produccion-de-acero/*

production by means of recycling.

The Spanish steel industry is at the lead in environmental performance, which has been addressed from several forefronts. Particularly, the efficiency of raw materials utilisation, the water and energy consumption, so as the reduction of CO_2 emissions and process waste valorisation, have been key strategic lines in the sector to improve its environmental impact and process sustainability.

The reduction of GHG emissions has been one of the main concerns of the iron & steel sector in the past decades. Since 1970, the Spanish steel sector has reduced CO_2 emissions per ton of steel produced by more than 75%, and in the last 20 years the reduction has been 50%[11]. The current available technologies have been already optimised to its limit in order to reduce the gas emissions, however, new technology developments are required to reach the objectives established in the short and long term.

For this reason, the iron & steel industries, the sector association (UNESID) and the Spanish Technology Steel Platform (PLATEA) have established a strong alliance in order to promote R&D&I initiatives in the sector.

4.2 Non-ferrous metals

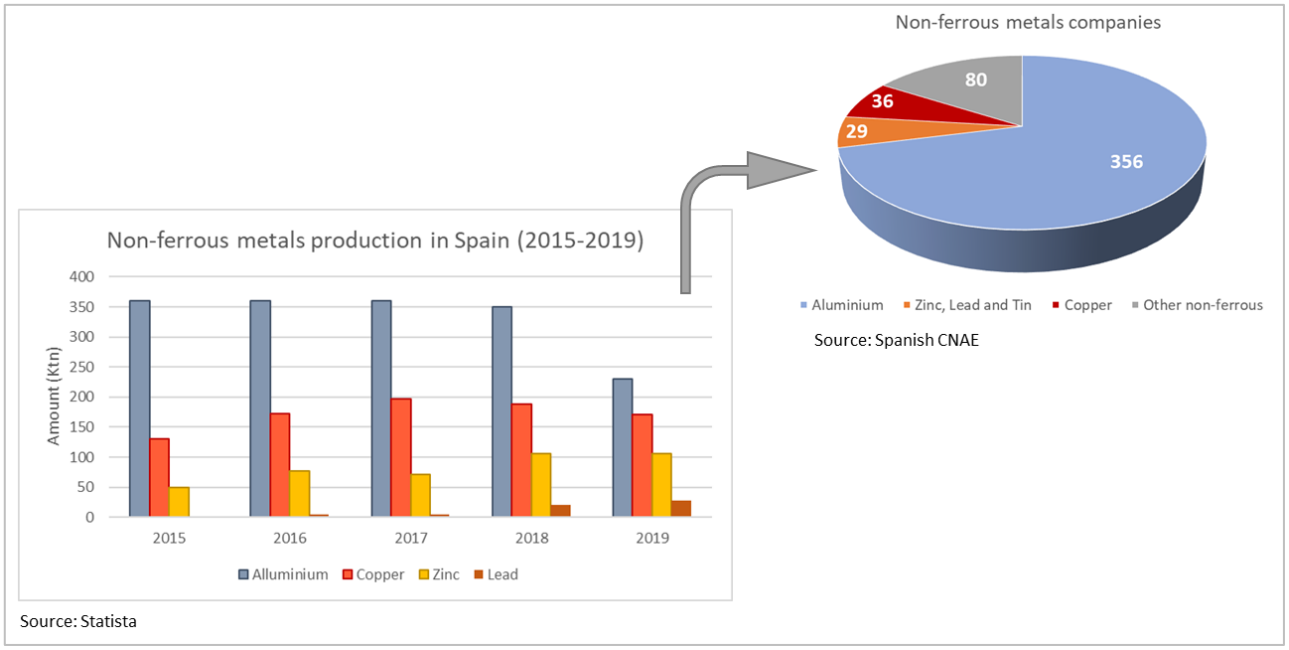
In addition to ferrous-based materials, Spain also stands out in the production of non-ferrous metals, such as aluminium, copper, zinc and lead. Among them, aluminium was the most relevant one in the past years, producing more than 350,000 tons/year. However, its production has lost some importance in the past years, the non-ferrous metals sector balancing and reducing the differences with copper, zinc and lead [12] [13] [14] [15].

According to the Spanish Association of Aluminium and Surface Treatments (AEA in Spanish), the Spanish aluminium industry covers all stages, from alumina production to recycling, and is in a leading position in Europe due to its reality and its capacity for growth. There are 292 companies dedicated to this metal, 31 of them focus their activity on the production of primary and recycled aluminium, whereas the rest 261 consist of transformation companies [16].

[11] Sustainability, UNESID. Available on: https://unesid.org/sostenibilidad/
[12] Annual evolution of aluminium production in Spain 2011-2019. Available on: https://es.statista.com/estadisticas/822214/produccion-de-aluminio-en-espana/
[13] Annual evolution of cupper production in Spain 2011-2019. Available on: https://es.statista.com/estadisticas/822219/produccion-de-cobre-en-espana/
[14] Annual evolution of zinc production in Spain 2011-2019. Available on: https://es.statista.com/estadisticas/823143/produccion-de-zinc-en-espana/.
[15] Annual evolution of lead production in Spain 2011-2019. Available on: https://es.statista.com/estadisticas/823126/produccion-de-plomo-en-espana/
[16] Spanish Association of Aluminium and Surface Treatments (AEA). Available on: https://www.asoc-aluminio.es/

Nonetheless, according to the Spanish CNAE-2009 code, the numbers are slightly different, showing 356 registered companies in this sector [17]. In the meantime, CNAE-2009 register includes a total of 29 companies dedicated to the production and transformation of zinc, lead and tin and 36 to copper.

Figure 7. Non-ferrous metals industrial landscape in Spain



5 Non-metallic materials sector

The production of non-metallic materials is the third EII sector that more energy consumes in Spain. According to the CNAE-2009 classification, this category is very wide and includes manufacturing activities related to a single mineral substance. For practical purposes, this report will analyse separately the cement, lime and gypsum sector. Glass and ceramic-based products, also included in this CNAE category, will be detailed in a dedicated section.

5.1 Cement

The Spanish cement sector consists of 9 business groups and 33 integral factories and has a clinker production capacity of 32.5 million tons per year. The Spanish Association of cement manufacturers in Spain (OFICEMEN) [18] has reported 35 cement production plants in Spain (see Figure 8).

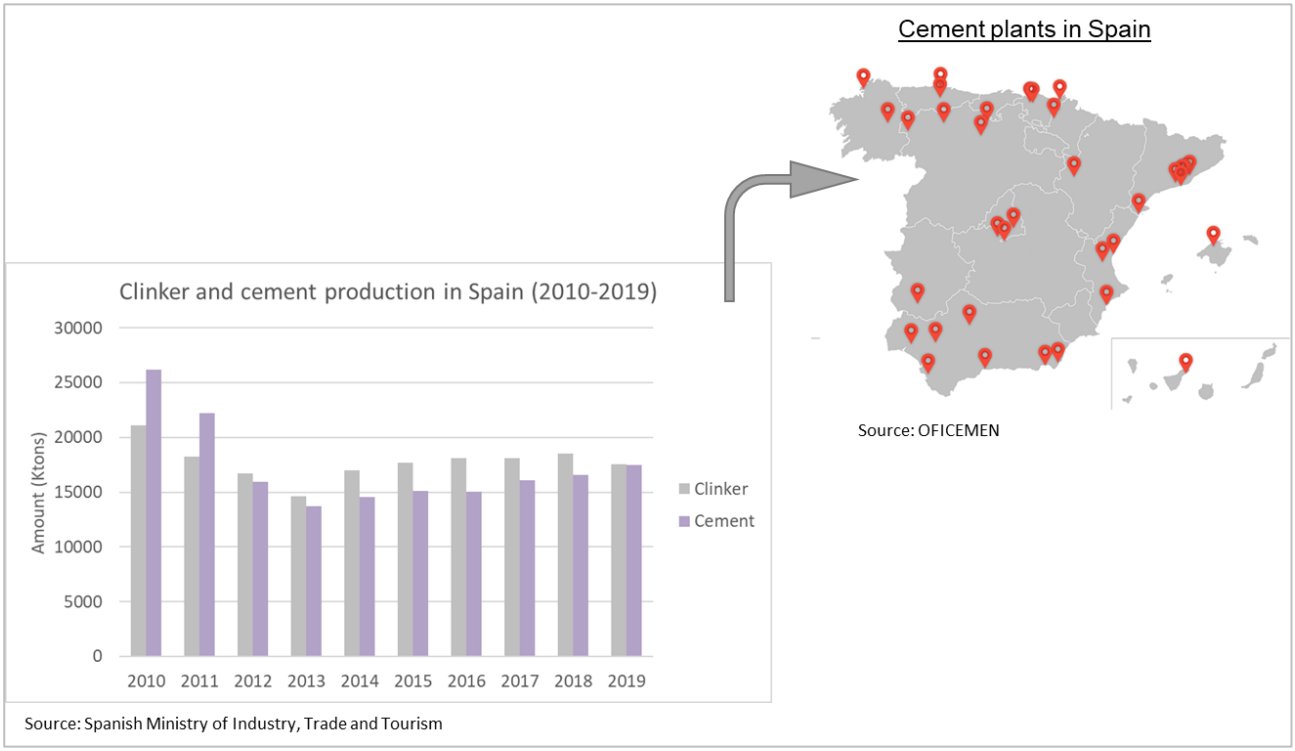
The production of clinker and cement has varied in the past 10 years, mainly due to the building

[17] Economic activity CNAE, Iberinfirom. Available on: https://www.iberinform.es/informacion-de-empresas/directorio-cnae/244/produccion-de-metales-preciosos-y-de-otros-metales-no-ferreos
[18] Cement factories in Spain, OFICEMEN. Available on: https://www.oficemen.com/el-cemento/fabricas-cemento-espana/

sector crisis occurred in 2008. However, it reached almost 17,000 Ktons in 2019 [19] and it is expected to reach in 2022 the same production level as the one in 2010 [20].

Thus, cement sector is one of the most relevant EII sectors in Spain, it being one of the most pollutant ones in terms of GHG emissions and with higher thermal energy demand. Consequently, and in line with the European initiatives, the national cement sector is constantly seeking for new and innovative solutions to decarbonise its processes.

Figure 8. Cement sector landscape in Spain



5.2 Lime

'Lime' is a generic term that designates all the physical forms of calcium and magnesium oxides, known as quicklime and calcined dolomite. Lime is a widely used product, e.g. as a flux in steel refining, as a binder in construction, in the sugar production industry or in pulp and paper production. construction, in the sugar production industry or in the manufacture of pulp and paper. It is also used in waste-water treatment to precipitate impurities or as an acid neutraliser in industrial liquid and gaseous effluents. It may be produced in lime factories, in which case it is called commercial lime, or in factories of various kinds for use as an intermediate product in the manufacture of paper pulp.

[19] Cement statistics. Spanish Ministry of Industry, Trade and Tourism. Available on: https://industria.gob.es/es-es/estadisticas/Paginas/Estadistica-Cemento.aspx
[20] Ministry of industry, "*AGENDA SECTORIAL DEL SECTOR CEMENTERO ESPAÑOL*," 2018.

The lime production in the last five years, according to the National Association of Lime and Lime Derivatives Manufacturers of Spain (ANCADE) reports, varied between 1.7 and 1.8 million tons of produced lime. By products, the supply presents the following order: 75% quicklime (oxide of lime, CaO), 20% hydrated or slaked lime (hydroxide of lime, $Ca(OH)_2$), and 5% calcined dolomite [21].

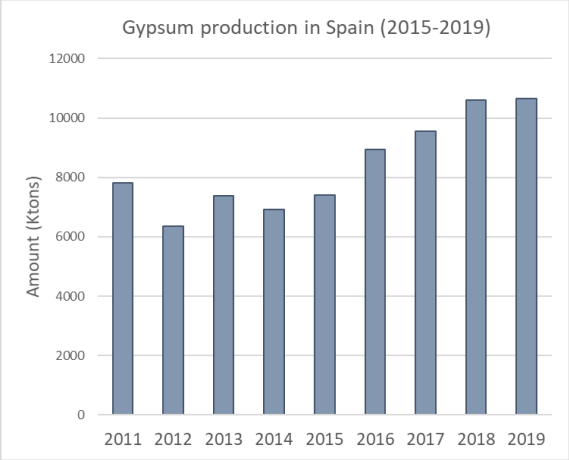
5.3 Gypsum

Gypsum has been with mankind since time immemorial and is one of the oldest building materials. Pure gypsum is a white mineral, but due to impurities it can turn grey, brown or pink. Chemically it is called calcium sulphate dihydrate ($CaSO_4$- $2H_2O$). Currently, its applications are wider, not only in the building sector, but also in ceramics, agriculture, chemical and pharma sectors, among others.

Gypsum is a fully recyclable natural material, allowing the material to be reintroduced into the life cycle without losing its exceptional characteristics. But it is also a mineral that is considered a non-renewable resource.

Gypsum production, both the extraction and the production and marketing of this product, is developed by multinational business groups, such as: Knauf, Saint Gobain and Lafarge, COEMAC, the former Uralita group. Its production has been increasing in the past years, reaching more than 10,000 Ktons in 2019 (Figure 9).

Figure 9. Gypsum production in Spain (2011-2019). Source: Statista [22]

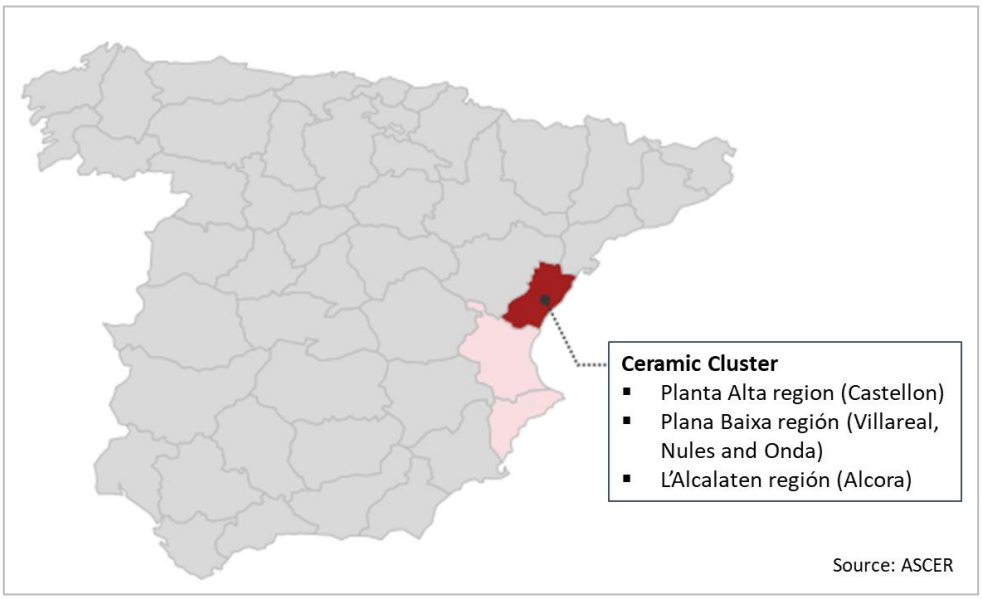


[21] National Association of Lime and Lime Derivatives Manufacturers of Spain (ANCADE). Available on: https://www.ancade.es/asociacion/
[22] Annual evolution of lead production in Spain 2015-2019. Available on: https://es.statista.com/estadisticas/823193/produccion-de-yeso-en-espana/

6 Ceramic sector

The Spanish ceramic sector manufactures two main products: (1) tiles and (2) frits, glazes and colours. Its activity is concentrated in Castellon region, where 95% of the national production is located. It characterised by the variable size of the companies (a large proportion of these companies are SMEs) and the wide range of products.

Figure 10. Ceramic manufacturing sector in Spain [23].



Tile manufacturing industry is one of the most dynamic and innovative in Spain and, within the global ceramic tile sector, is a leader in terms of technological development, design and quality of service. The ceramics sector is the third industry that contributes the largest surplus to Spain's trade balance.

In 2019 the total contribution of the ceramic tile manufacturing sector to the Spanish economy was 3,824 million euros, equivalent to 2.7% of industrial GDP and 0.34% of Spanish GDP. Since 2012, it has had a compound annual growth rate of 3.4%, although in 2019, the production fell by 3.8% compared to the previous year to 510 M m^2. In terms of turnover, the sector has been increasing its sales at a compound annual rate of 5.1% since 2012. This demonstrates the sector's high growth capacity and its importance in the growth of the provincial and regional economy. In 2019, despite the fact that production decreased by 3.8%, the total turnover increased by 4.5%, showing an increase in the value of the ceramic in the value of the ceramic product[23].

[23] *Socio-economic and fiscal impact of the ceramic tile sector ceramic tiles and floor tiles in Spain*, ASCER. December 2020. Available on: https://transparencia.ascer.es/media/1039/informe-impacto-socioeco-sector-cer%C3%A1mico_ascer.pdf

In 2019, this sector was made up of 248 companies. Annual production amounts to 510 million m^2 of tiles, more than 3,700 million euros turn over and with global CO_2 emissions of 2.9 million tons and a volume of free allowances of 2.5 million tons.

As for the frits, glazes and colours sector, Spanish industry is a global leader. According to the national sector association, Anffecc, this industry achieved more than 1,500 million euros turnover in 2021, reaching their own record[24], it confirming their key role in the national and international market.

Figure 11. Turnover of frits, glazes and colourants industry in Spain [24]



7 Glass sector

The glass sector in Spain is characterised with an annual production over 3.7 million tons and a turnover of about 2,000 million euro [25].

Figure 12 shows the location of the glass companies belonging to ANFEVI.

[24] National Association of frits. Available on: *www.anffecc.com*
[25] VIDRIO España. Available on: *www.vidrio.org*

Figure 12. Location of the glass companies in Spain from ANFEVI



This industrial sector is represented by different associations, depending on the final product. Particularly, VIDRIO ESPAÑA is the national association for the glass industry, and it is made up of companies belonging to the following national associations: AFELMA (manufacturers of insulating mineral wool), ANFEVI (manufacturers of glass), FAOVI (glass manufacturers domestic, moulded, insulators and jars) and FAVIPLA (flat glass manufacturers).

8 Pulp and paper sector

In 2020, the total Spanish production was 7.9 million tons, which are distributed in 1.7 million of pulp and 6.3 million of paper and cardboard. There are 10 pulp mills and 69 paper and cardboard factories in Spain. The Spanish industry is the sixth largest producer in the EU of paper and the fifth largest producer of pulp. The turnover in 2020 was 3,981 million euros [26].

In Spain, a multitude of types of paper are produced according to their specific application. The most important are:

- Newsprint and printing and writing paper that is used for the manufacture of books,

[26] ASPAPEL. Available: on www.aspapel.es

newspapers, and magazines.

- Tissue paper aimed at sanitary and hygienic use.
- Corrugated cardboard papers that constitute the different layers with which cardboard boxes are made.
- Coated cardboard used in folding cases and lightweight packaging.

Virgin cellulose is used in the production of printing and writing papers, in toilet and sanitary papers and in certain special papers. On the contrary, recycled fibre is the fundamental raw material in the production of newsprint and packaging papers. As important characteristics of the Spanish industry, we can mention, among others:

- the production of bleached cellulose based on short fibre, using eucalyptus, a fast-growing species, thanks to the favourable climatic conditions of the Iberian Peninsula, and
- the high degree of use of paper for recycling, with a Utilization Rate of 82%: the Spanish industry is the fourth most recycled in Europe, surpassed only Germany, France, and Italy.

Of the nearly eighty factories spread throughout the national territory, the geographical areas with the greatest paper implantation are Aragon, Catalonia, the Basque Country, Navarre, Castilla y León and the Valencian Region as shown in Figure 13.

Figure 13. Location of the Spanish pulp & paper industry in Spain. Source: ASPAPEL [26]




Toulouse
Montpell
Gijón
Oviedo
Santiago de Compostela
Vigo
Oporto
Aveiro
Coimbra
Salamanca
Portugal
Cáceres
Lisboa
Badajoz
Toledo
España
Zaragoza
Tarragona
Palma
Alicante (Alacant)
Elche
Murcia
Córdoba
Sevilla
Huelva
Albufeira
Faro
Málaga
Almería
Gibraltar
Mar de Alborán
Argel
مدينة الجزائر
Mar Balear

9 Renewable energies uptake by sector

There are different decarbonisation strategies suitable for these EIIs, whose potential relies on the industrial process requirements and energy demand, both heat and electricity.

Particularly, this report approaches those strategies related to the uptake of renewable energies d, in addition to CCS/CCSU and measures to improve the process efficiency energy. The most relevant decarbonisation pathways of each sector are described in the following sections. A final summary is detailed in

Table 1.

No specific decarbonisation actions related to alternative feedstocks or materials are addressed.

9.1 Chemical and petrochemical sector

The decarbonization of both chemical and petrochemical industries rely on similar pillars. Due to the high variety of processes in these industries, different approaches can be followed for the achievement of net neutral emissions:

- Switching fuels for heat production: zero-carbon hydrogen or biomass can mitigate emissions with limited alterations to the furnace design and production setup. The development of e-fuels from CO_2 and green H_2 will play also a key role in the long-term REs uptake strategy.
- Switching fuels for heat production to zero-carbon electricity, although this would require significant changes to production equipment.
- Improving the energy efficiency and intensification of the processes by integration of heat-exchanges between different process units, and increasing the heat recovery
- Advancing the CCS/CCUS technologies for the conversion of CO_2 into valuable compounds.

9.2 Metallic sector

9.2.1 Ferrous metals

For primary steel making and for the integral route there are two main technological pathways for CO_2 reduction: Smart Carbon Usage (SCU) and Carbon Direct Avoidance (CDA). These pathways, seek to reduce the use of the carbon compared to the current means of steel production or to avoid carbon emissions entirely.



On the one hand, Smart Carbon Usage (SCU) involves:

- CCSU, which includes all the options for using the H_2, CO and CO_2 in steel plant gases or fumes as raw materials to produce, or integrate into, valuable products. The use of biomass with CCU could be an option as well.
- Process integration, which looks at modifications of existing ironmaking/steelmaking processes based on fossil fuels that would help reduce the use of carbon, and thus the CO_2 emissions.

On the other hand, Carbon Direct Avoidance (CDA) includes:

- Hydrogen-based metallurgy, which uses hydrogen to replace carbon as the main reduction agent for the iron ore reduction stage.
- Electricity-based metallurgy, which uses electricity instead of carbon as reduction agent for the iron ore reduction, with greater focus on renewable energy. The electrolytic process is in an early development phase.

9.2.2 Non-ferrous metals

In the case of non-ferrous metals, the REs uptake is very aligned with the iron & steel sector strategy:

- Green hydrogen could play a key role as an energy vector by substituting natural gas. However, it needs to be verified whether hydrogen will affect to the final product quality, as in the case of aluminium product, since currently the maximum content of hydrogen in the aluminium is a key specification.
- Optimise production process efficiency
- Capture the CO_2 emissions from the production process (CCUS)

9.3 Non-metallic materials

The REs uptake pathway is common in the case of cement, lime and gypsum industries:

- Switching to a zero-carbon fuel would mitigate CO_2 emissions from fuel combustion. biogas or biomass would require a modest retrofit of the kiln. Replacing conventional fuel with hydrogen would require redesign.
- Applying CCSU:
- Optimise production process efficiency



9.4 Ceramics

Similar strategies are followed in both tiles and frits, glazes and colourants industries. A switch to renewable energy will be done gradually and will depend on the type of plant and local availability options, some plants could switch to decarbonised electricity whilst others could eventually use biofuels, green hydrogen, or green synthetic gas. There are several options:

- Alternative green fuels. The use of biomethane could be implemented but it is insufficient for the sector demand. Hydrogen is a most suitable option. Efforts are focused on the modifications that must performed in the burners to exceed between 5 and 20% hydrogen substitution. Hydrogen use will lead to a higher generation of NOx due to an increase in adiabatic flame temperature. The influence of the integration of this new energy vector on product quality is still under investigation, although first results show that it does not affect the quality of the tiles [27].
- Total or partial electrification of the processes.
- Efficiency improvements such as the recovery of excess heat to reduce fuel consumption.
- Even if carbon capture use and storage (CCUS) is at a high TRL, it would not be a viable option due to the low CO_2 concentration in the emission gases.

9.5 Glass

REs uptake of the glass sector comes the following main directions:

- Switch to alternative green fuels, such as green hydrogen, biogas, synthetic methane
- Process electrification.
- CCSU could be option to explore depending on site specific conditions.

9.6 Pulp and paper

Energy efficiency measures, the use of biomass as fuel and cogeneration are currently the three pillars of the strategy of the sector in Spain in in terms of CO_2 emissions reduction. In addition, Cogeneration for hydrogen use is at almost commercial TRL with some turbine manufactures being able to include hydrogen in their installations.

[27] Ayming, “Ruta hacia la descarbonizacion de la industria ceramica,” [Online]. Available: *https://www.ayming.es/insights-y-noticias/eventos/ruta-hacia-descarbonizacion-industria-ceramica/*.



Table 1. Most relevant strategies for emissions reduction in different EII sectors – Spain

Petrochemical & Chemical	Metallic (Ferrous and non-ferrous)	Non-metallic materials	Ceramics	Glass	Pulp & Paper
Alternative fuels (hydrogen, biomass)	Alternative fuels (hydrogen)	Alternative fuels (biogas, biomass)	Alternative fuels in furnaces (hydrogen)	Alternative fuels in furnaces (hydrogen, biogas, synthetic methane)	Alternative fuels (hydrogen, biomass)
Electrification	Electrification	CCSU	Electrification	Electrification	CHP (also H_2 CHP)
Improving process integration and efficiency	Improving process integration and efficiency	Improving process integration and efficiency	Improving process integration and efficiency	CCSU	
CCS/CCSU	CCSU				

10 Challenges and potential measures

10.1 Decarbonizing electricity – Renewable PPAs

More than half of the electricity generated in Spain is not governed by electricity market prices because, before as soon as it is generated, this electricity already has an owner who has signed a purchase contract at a predetermined price. Electricity-intensive companies and industries often enter into such bilateral agreements in order to secure a lower and more stable price over time. Among these bilateral agreements are those known in the industry as PPAs (Power Purchase Agreements).

PPAs are a reality in the Spanish electricity market. Despite the high electricity prices, Spain is crowned leader in the European PPA market for yet another year, with almost 4 gigawatts (GW) of contracted capacity in 2021. As revealed in the latest report by Swiss consultancy Pexapark, the 34 agreements signed represent a third of the capacity accumulated across Europe during the year and surpass the record levels recorded in 2019 [28].

The Spanish RDL 24/2020 echoes this reality and sets out the legal reality and establishes the legal regulatory framework necessary to cover the risks of medium and long-term energy supply contracts. This is particularly beneficial to the EIIs, since they can assure a renewable energy supply in the long-term, with fixed and competitive prices [29].

Particularly, The so-called 'FERGEI' (Spanish Reserve Fund for the Guarantees of Electro-intensive Entities), regulated by the before mentioned RDL 24/2020, is a body attached to the Spanish Ministry of Industry, Trade and Tourism, that has been created to cover on behalf of the State, the potential risks from medium- and long-term purchases and sale transactions for the supply of electricity between electricity consumers (who are electro-intensive consumers) and the various electricity suppliers in the production market.

However, despite this apparently favourable framework, PPAs are a bit far from being a recurrent solution for decarbonising electricity in EIIs in Spain. The current increase of electricity price and the volatility of the electrical sectors have slowed down the contract of PPAs. PPAs prices have increased by 27.5% in the last year in Europe (8.6% in the first quarter of 2022). They are currently

[28] *España, líder en PPAs con un tercio de la capacidad europea contratada en 2021*. El Economista. February 2022. Available on: https://www.eleconomista.es/empresas-finanzas/noticias/11615601/02/22/Espana-lider-en-PPAs-con-un-tercio-de-la-capacidad-europea-contratada-en-2021.html

[29] *Claves de los "PPA" o contratos de suministro de energía renovable a largo plazo*, CUATRECASAS. Available on: https://www.cuatrecasas.com/resources/legal-flash-energia-claves-de-los-ppa-o-contratos-de-suministro-de-energia-renovable-a-largo-plazo-power-purchase-agreements.%20rd-ley%2024_2020-611f7f1586180923779452.pdf?v1.6.0.202110071014

around 57 euros per MWh on average, according to LevelTen, which is still significantly lower than the electricity market [30].

Even before the energetic crisis derived from the war conflict in Ukraine, the Spanish EIIs association already published a manifesto, calling on the Spanish Government to adopt and promote short-term measures to overcome the high electricity prices suffered by the electricity [31].

All this scenario translates in a not too much promoted PPAs adoption by the EIIs. Particularly, according to AEGE, only 10% of their associates have signed a PPA for 10-40% of their consumption with a duration of 5 to 10 years. Some examples are showed in Table 2.

Table 2. Examples of corporate renewable PPAs for Spanish EIIs

Industry	Sector	Technology	Capacity (MW)	Duration (years)	↓kt CO2	Year
Alcoa	Aluminium	Wind	906	10	Undisclosed	2024
Sidenor	Steel	Wind Solar PV	350	10		2021
Air Liquide	Chemicals	Undisclosed	15 %	10	250	2020
Tubos Reunidos SA	Steel tubes	Wind	1200	10	Undisclosed	2022
Bayer	Pharmaceutical	Solar farm	590	10	245	2022

10.2 Main challenges

Some of the most challenges have been detected through the contribution of the RE4Industry collaborative network, particularly, thanks to the Spanish Cluster & Committee:

Table 3. Main challenges detected in EII sector in Spain

LEGAL	➢ Development of specific regulation for by-products as feedstocks. There are legal issues related to difficulties to use/transport secondary-raw materials. Sometimes it is not possible to use some residues because they do not fulfil the waste law. ➢ Alternatives to produce electricity, in addition to renewable sources, such as nuclear power.

[30] "*Las compras directas de electricidad se estrellan*", La Vanguardia. April 2022. Available on: https://www.lavanguardia.com/economia/20220417/8199949/electricidad-luz-compras-directas-ppa.html

[31] "*AEGE impulsa un manifiesto por la industria electrointensiva española*", AEGE. December 2021. Available on: *https://www.aege.es/2021/12/aege-impulsa-un-manifiesto-por-la-industria-electrointensiva-espanola-con-la-adhesion-de-comunidades-autonomas-sindicatos-asociaciones-de-empresas-industriales-camaras-de-comercio-ayuntamientos/*

	Nuclear power could play a role in the national electric landscape. Extend of the nuclear power plants life to secure the stabilization of electricity production.
SOCIAL	➢ Development of specific certifications for green products. This would increase awareness of these products among final consumers and promote the production of circular added-value products and services. ➢ Public recognition by official bodies. Acquisition of renewable energy should have more recognition by the authorities to stand out those EIIs that have put in place initiatives to decarbonize their processes.
FINANCIAL	➢ Lack of funding options There will be new costs related to the development of green energies in the EIIs facilities. E.g. for green hydrogen, its transport is a challenge. There is uncertainty among EIIs about the current infrastructure that transports natural gas, which might be as well employed in the future to transport green hydrogen to the companies' site. How will the cost derived of this type of infrastructure be financed? ➢ Such type of infrastructure will allow to drive other projects (e.g., biofuels) required for the decarbonisation of industrial processes ➢ Saturation of electrical connection points in the network can be expected. Thus, investments will be required for the development of a new distribution system to buy/sell more electricity form the network
TECHNICAL	➢ Fuels availability Some EIIs might need huge amounts of fuels. Assuring its supply will be a challenge, especially those produced from by-products os residues (eg. Biomass, biogas) ➢ Retrofitting options Integration of some technologies in current facilities, so-called as retrofitting, might be not so obvious in some cases. ➢ Influence on final product quality. Some industries, such as the aluminium or the ceramic sectors, are already evaluating how certain renewable energies adoption could interfere on the final product quality ➢ Lack of infrastructure Transport and supply of alternative fuels might be a challenge. For example, for green hydrogen, its transport is a challenge. There is uncertainty among EIIs about the current infrastructure that transports natural gas, which might be as well employed in the future to transport green hydrogen to the companies' site.