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Part 2: Major greenhouse gas emitting sectors
Sectors

Chapter 3-2

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3.2 Major process industries

3.2.1 Steel

The steel industry operates in all parts of the world, processing a range of products that were sold for a total value of US$2.5 trillion in 2019. In 2017, the industry employed more than six million people worldwide.[44] For every US$1 of value created by working in the steel industry itself, a further US$2.50 of value is supported in other sectors of the global economy through the purchase of raw materials, goods, energy and services. For every two jobs in the steel industry, 13 more jobs are supported throughout the supply chain - meaning that a total of about 40 million people worked in the global steel industry supply chain in 2017.[45] According to this analysis by Oxford Economics, the global steel industry contributed between 4 % and 10 % to global GDP in 2017.

The construction sector is one of the most important steel-using industries, accounting for more than 50 % of global steel demand.[46] Steel finds its application in a number of important infrastructures such as bridges, offshore oil platforms, civil engineering and construction machinery, railway wagons, tanks and pressure vessels, nuclear, thermal and hydroelectric power plants.

3.2.1.1 Presentation of global production volumes and emissions

Global steel production has more than tripled in the last 50 years, even though countries like the US and Russia have cut back on domestic production and rely more on imports. In the early 1960s, global steel production was dominated by the US, Europe and the USSR (see Figure 1). China overtook Japan in the early 1990s to become the leading steel producer. In the meantime, China

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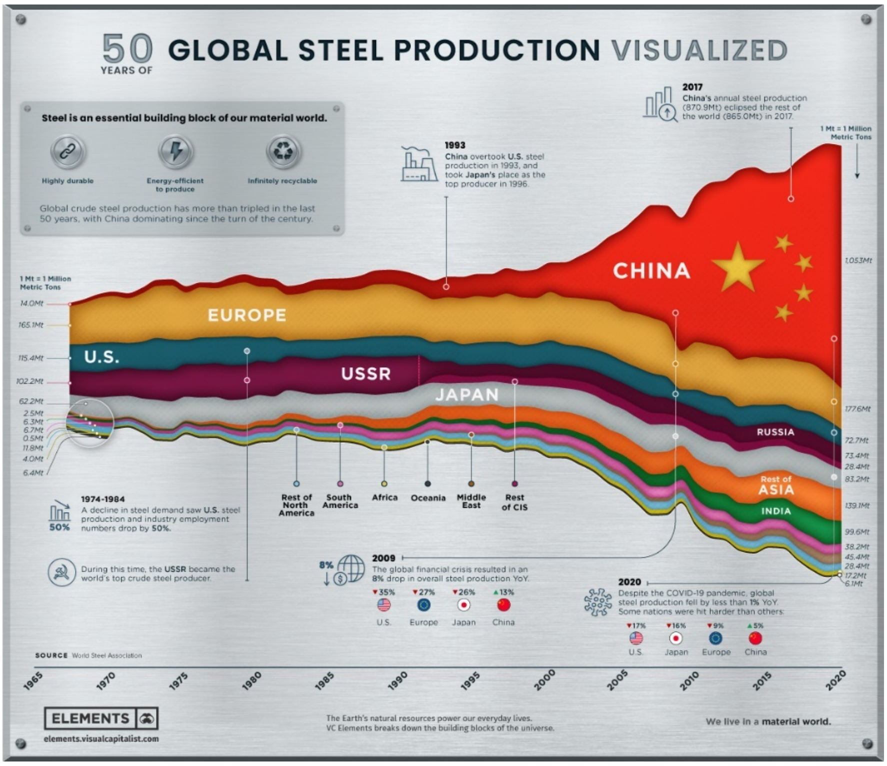
[44] Cf. Oxford Economics, 2019.
[45] Cf. Oxford Economics, 2019.
[46] Cf. World Steel Association, 2022.

and India have steadily increased their production to become the world's two largest steel producers in 2021.



Steel is an essential building block of our material world.

Global crude steel production has more than tripled in the last 50 years, with China dominating since the turn of the century.

1993 China overtook U.S. steel production in 1993, and took Japan's place as the top producer in 1996.

2017 China's annual steel production (870.9Mt) eclipsed the rest of the world (865.0Mt) in 2017.

1974-1984 A decline in steel demand saw U.S. steel production and industry employment numbers drop by 50%.

During this time, the USSR became the world's top crude steel producer.

2009 The global financial crisis resulted in an 8% drop in overall steel production YoY.

2020 Despite the COVID-19 pandemic, global steel production fell by less than 1% YoY. Some nations were hit harder than others:

SOURCE World Steel Association

The Earth's natural resources power our everyday lives. VC Elements breaks down the building blocks of the universe.

We live in a material world.

Figure 1 : Developments in global steel production over the last 50 years.

Source: Visual Capitalist, 2021.

The first source of emissions in the steel industry is the extraction of iron ore from the ground. Studies assume emissions between 9 and 13 kg/t iron ore.[47] Life cycle analyses of mines in China found higher emissions of 270 kg/t on average, with a 90 % confidence interval of 210 to 380 kg/t.[48]

There are four main types of iron ore deposits: massive hematite, which is the most commonly mined, magnetite, titanomagnetite and pisolitic ironstone.[49] The extraction of magnetite requires 0.3 GJ/t of ore and the extraction of haematite requires half of that.[50] Coke production is an important part of integrated iron and steel plants using the BF-BOF route, as it serves as a reducing agent and thermal energy source. In modern blast furnaces, 460-480 kg of reducing agent is required per ton of pig iron, while the global average is 500 kg/t of pig iron. In modern blast furnaces with additional fuel injection, coke consumption can be less than 300 kg/t of pig iron.[51] Coke is produced by heating coking coal to 1000 to 1200 °C for several hours in coke ovens to drive out volatile compounds and moisture. Each ton of coke consumes about 3.5 to 5.0 GJ of energy and about 1.6 tons of coking coal. Coke production accounts for about 10 % of the energy demand in a BF-BOF plant.

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[47] emissions correspond to CO_2 emissions; cf. Michael et al., 2018.
[48] Cf. Gan & Micheal, 2017.
[49] Cf. BHP, 2022.
[50] Cf. Engeco, 2021.
[51] Cf. Industrial Efficiency Technology Database, 2022.

According to the World Steel Association (WSA), the emission intensity in the production of steel from iron ore was 1.89 t/t of crude steel and the water consumption was 3.3 m^3 /t of crude steel.[52] Depending on the steel production process, between 10 and 20 GJ per t of crude steel are required for production. Total global steel industry production in 2021 was 1,890 Mt of crude steel, resulting in 2.6 Gt of operational CO_2 emissions. Table 1 summarises all important figures of the steel industry.

Parameter	Values
Emissions from iron ore extraction	9-13 kg-CO /t-iron-ore$_2$ In China 270 kg-CO /t-iron-ore$_2$
Energy consumption for the extraction of magnetite (Fe_3O_4)	0.3 GJ/t-iron ore • *Promotion through the use of diesel – 41 $* • *Crushing - 43 %* • *Other processing - 16 %*
Energy consumption for the extraction of hematite (Fe2O3)	0.15 GJ/t-iron ore • *Promotion through the use of diesel - 90* • *Other processing - 10*
Coke demand	Approx. 500 kg-coke/ t pig iron
Energy demand for coke production	3 to GJ/t-coke 1.6 t-coal/ t-coke
Emission intensity of steel (2020)	1.89 t-CO /t-raw steel$_2$
Energy intensity	For the blast furnace Approx. 20 GJ/ t crude steel For direct reduction (natural gas + electric furnace) Approx. 15 GJ/ t crude steel, basis iron ore For the route (electric furnace) Approx. 9 GJ/ t crude steel, scrap basis
Water consumption (2019)	3.3 m /t-raw-steel^3
Total steel production (2021)	1,951 Mt
Total emissions (2021)	2.6 Gt CO_2

Table 1 : Summary of important figures of the global steel industry.

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[52] Cf. World Steel Association, 2022; Wenqiang et al., 2019.

3.2.1.2 Sources of CO emissions$_2$

The first step in ferrous metallurgy is to heat the ore to remove water and break down the calcium carbonates into oxides, known as sintering. The oxides are then reduced in a blast furnace into which the roasted ore (sinter), coke and limestone are continuously fed from above. [53][54] The molten iron and slag are removed from the bottom. Near the bottom of a furnace are nozzles through which preheated air is blown into the furnace. As soon as the air enters, the coke in the area of the nozzles is oxidised to carbon dioxide, releasing great heat. The hot carbon dioxide flows upwards through the layer of hot coke above, where it is reduced to carbon monoxide. The carbon monoxide serves as a reducing agent in the upper areas of the oven. In the upper area of the oven, iron oxides are reduced. In the middle section, limestone decomposes and the resulting calcium oxide combines with the silica and silicates of the ore to form slag. The various chemical reactions that take place in the blast furnace are shown in Figure 2 Figure 2.

Oxygen steelmaking, also known as *Linz-Donawitz steelmaking*, is a primary steelmaking process in which high-carbon molten pig iron from the blast furnace is processed into steel. [55] By injecting oxygen into molten pig iron, the carbon content of the alloy is lowered and converted into low-carbon steel. The *Linz-Donawitz* process is known in English as the *Basic Oxygen Furnace because fluxes of* burnt lime or dolomite, which are chemical bases, are added through the bottom to promote the removal of impurities and protect the lining of the converter.[56] The energy requirement of BF-BOF* is 18.8 GJ/t-HRC.[57]

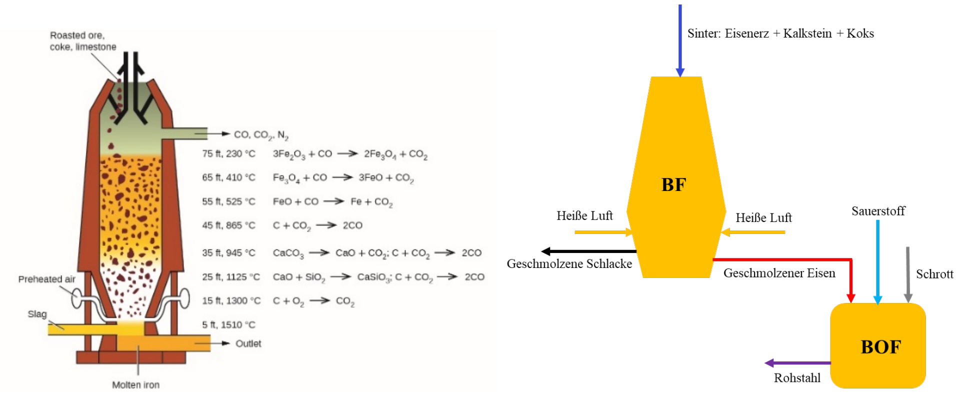

Figure 2 : Different chemical reactions in a blast furnace (left). Summary of the blast furnace oxygen top blow converter route for steel production. BF - Blast Furnace. BOF - Basic Oxygen Furnace.

Source: Libretext Chemistry, 2020.

Direct reduction of iron ore is the conversion of solid iron ore (so-called iron ore pellets) into metallic iron without conversion to the liquid phase. Most direct reduced iron (DRI) is produced by reacting

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[53] BF - Blast Furnace
[54] Limestone consists predominantly of $CaCO_3$
[55] BOF - Basic Oxygen Furnace
[56] Cf. Wikipedia, 2022.
[57] Cf. Fabrice & Oliver, 2020.

iron oxide with hydrocarbon-based reducing gases from natural gas reforming or coal gasification.[58] DRI technology will produce 104 Mt globally in 2020.[59] With the falling price of shale gas, the construction of DRI plants in the US has taken off.[60] Shaft furnaces, rotary kilns, rotary hearth furnaces and fluidised bed reactors are used for direct reduction of iron ore. Most DRI plants use the shaft furnace reactors developed by MIDREX™ and HYL-Energiron. [61]

A simplified process flow of the direct reduction of iron ore is shown in Figure 3 is shown. The product of direct reduction is sponge iron, which is then fed into the electric arc furnace (EAF) for further processing. About a quarter of the steel produced worldwide is made using the EAF process,[62] which uses high current electric arcs to melt scrap steel and/or sponge iron and convert it into liquid steel. External arc heating provides better thermal control than the Basic Oxygen process.[63]

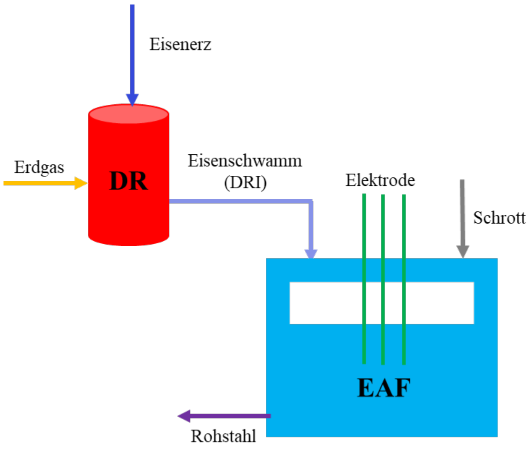

Figure 3 : Steel production by direct reduction with natural gas and electric arc furnace.

3.2.1.3 Technical options for CO_2 reduction

About 75 % of the iron produced worldwide is produced in blast furnaces, which is refined in an oxygen blast furnace. BF-BOF emissions are 1.6-2.0 t-CO_2 /t-steel, depending on the technologies used. The MIDREX NG™ direct reduction process combined with an EAF has the lowest CO_2 emissions of any commercially proven iron ore-based steelmaking route, with 1.1-1.2 t-CO_2 /t-steel. [64]

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[58] Syn-Gas
[59] Cf. MIDREX®, 2020.
[60] Cf. Reuters, 2013.
[61] Cf. Abhinav et al., 2020.
[62] Cf. Britanica, 2021.
[63] Cf. Britanica, 2021.
[64] Cf. MIDREX®, 2020.

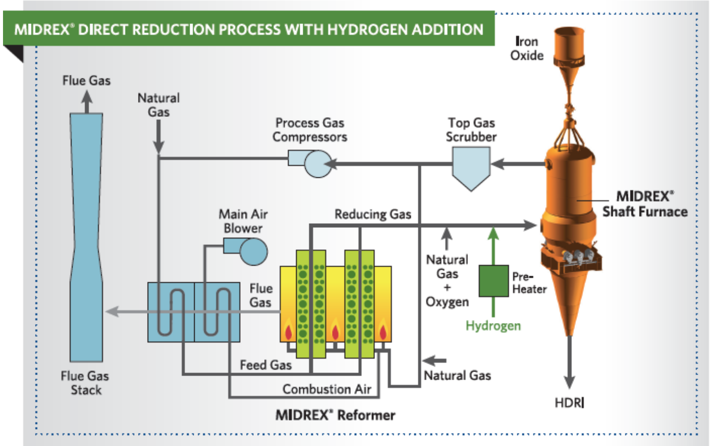

Figure 4: Direct reduction with MIDREX® process.

Source: MIDREX®, 2022.

According to Primetals and MIDREX®, the direct reduction electric arc furnace (DR-EAF) route, which uses natural gas in the DR process, can reduce carbon intensity for liquid steel by 60-70 % compared to the conventional BF-BOF route (see Figure 5). Using 'green' hydrogen instead of natural gas can reduce emissions on the same route by 85-90 % compared to the BF-BOF route.

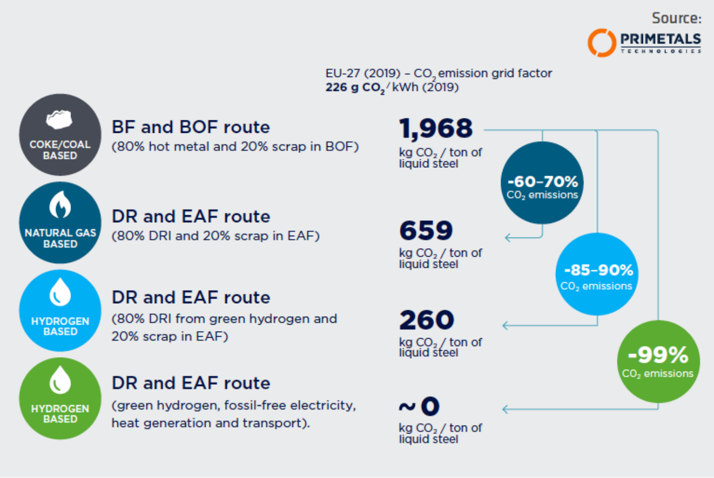

Figure 5 : Reduction of steel production emissions with the use of the MIDREX® process.

Direct reduction of iron ore with hydrogen requires 54-58 kg-H /t-iron-ore.$_2$[65] The sponge iron produced by this process is melted in an electric arc furnace. The net energy demand for this process is between 13 and 15 GJ/ t-HRC.[66] The electricity demand to produce hydrogen by water electrolysis is about 50 kWh/kg-H_2 . If sufficient green electricity were also available to operate the electric furnace, CO_2 emissions would be virtually eliminated.

The waste gas from the blast furnace usually contains about 20-30 % carbon monoxide and about 2-6 % hydrogen as combustible components as well as a considerable amount of inert gases with

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[65] Cf. Fabrice & Oliver, 2020.

[66] Cf. Fabrice & Oliver, 2020. HRC - Hot Rolled Steel

about 45-60 % nitrogen and 20-25 % carbon dioxide. [67][68] Due to the high proportion of inert gases and the already relatively low calorific value of the main combustible component CO, it has a lower calorific value in the range of 3-4 MJ/m^3.[69] So far, there is only limited experience with the use of carbon capture technology at the blast furnace. However, since this steel production route is considered to be the most important in the long term, with a share of about 70 % of pig iron production today, development work on the use of carbon capture technology in the blast furnace is essential. Acelor Mittal, BHP and Mitsubishi Heavy Industries have recently published a development cooperation on this. [70]

Application example

Well-known companies such as ArcelorMittal, Voestalpine, Tata Steel, SSAB and ThyssenKrupp have projects to be operational by 2030 to produce low-carbon steel, mainly in Europe, by replacing natural gas with green hydrogen in direct reduction furnaces. In addition, ThyssenKrupp and ArcelorMittal have announced projects in Duisburg and Dunkirk, respectively, to use blue hydrogen for the direct reduction of iron ore. Salzgitter has also planned demonstration projects for the production of green steel with green hydrogen. A comprehensive list of announced projects for production of the low-carbon steel is given in Annex 2.

3.2.1.4 Developmental relevance

According to the IEA, global steel demand is expected to increase by more than a third by 2050[71] The Covid 19 crisis has shaken global supply chains and led to an estimated 5 % decline in global crude steel production in 2020 compared to 2019. Process-related emissions can be reduced by using green hydrogen, low methane natural gas and carbon capture and sequestration. This requires the large-scale installation of wind and solar power plants to produce green hydrogen, the development of hydrogen transport infrastructure and the introduction of carbon taxes to encourage companies to adopt green alternatives for steel production.[72] In this task, developed countries can facilitate the introduction of these alternatives through know-how transfer.

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[67] Blast Furnace
[68] Cf. Huth & Heilos, 2013.
[69] Lower heating value of methane - 35.8 MJ/Nm^3
[70] Cf. Business Green, 2022.
[71] Cf. IEA, 2021.
[72] Cf. Argus, 2022.

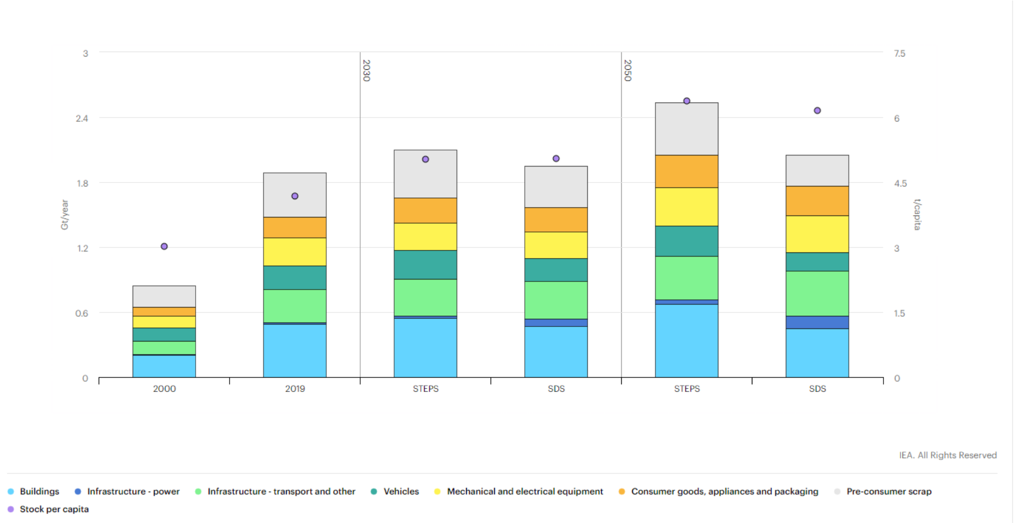

Figure 6: Global steel demand in 2050 according to IEA in Stated Policies and Sustainable Development scenarios.

Source: IEA, 2021.

However, the technical measures mentioned do little to reduce environmental degradation, water pollution and biodiversity loss from iron ore mining. In a study, the authors examined the spatial and temporal distribution of the mining of nine metal ores in around 3,000 mining sites worldwide between 2000 and 2019. [73]

It showed that 79 % of global metal ore mining in 2019 came from five of the six most biodiverse biomes, with mining volumes in tropical moist forest ecosystems doubling since 2000.[74] Chhattisgarh, for example, hosts some of India's most valuable forests, but is also an area rich in minerals such as iron ore. However, the race to extract these resources is devouring these forests. The latest data from the Chhattisgarh Forest Department shows that at least 4,920 hectares of forest land in the central Indian state have been diverted for iron ore mining in recent years.[75]

3.2.2 Cement

3.2.2.1 Presentation of global production volumes and emissions

One of the most important building materials in the modern world is concrete. In addition to gravel, sand and water, the production of concrete also requires cement as a binding agent. Although cement makes up only a small proportion of concrete mixtures (about 12 vol%), it is almost exclusively responsible for the CO_2 emissions produced.

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[73] Bauxite, copper, gold, iron, lead, manganese, nickel, silver and zinc

[74] Cf. Luckeneder et.al., 2021.

[75] Cf. Mongaby, 2021.

Since 1990, the worldwide production of cement has quadrupled from just over 1 Gt to more than 4 Gt. In 2021, just under 4.3 Gt of cement was produced worldwide. Since 2014, the production and consumption of cement has stabilised and is only growing slowly globally (Figure 7).

China dominates the global production of cement with over 50 % of the volumes produced. The country has produced about two-thirds of the world's total cement since 1990 and used it for the country's rapid industrialisation and urbanisation. Between 2011 and 2013 alone, China consumed more cement than the US did in the entire 20th century. Currently, Chinese production is stagnating or even slightly decreasing (Figure 8). India is the second largest producer with 8 % of the quantities.[76]

The European and North American cement plants in particular are often more than 30 years old, while the plants in China and other emerging countries are still relatively young (Figure 9).

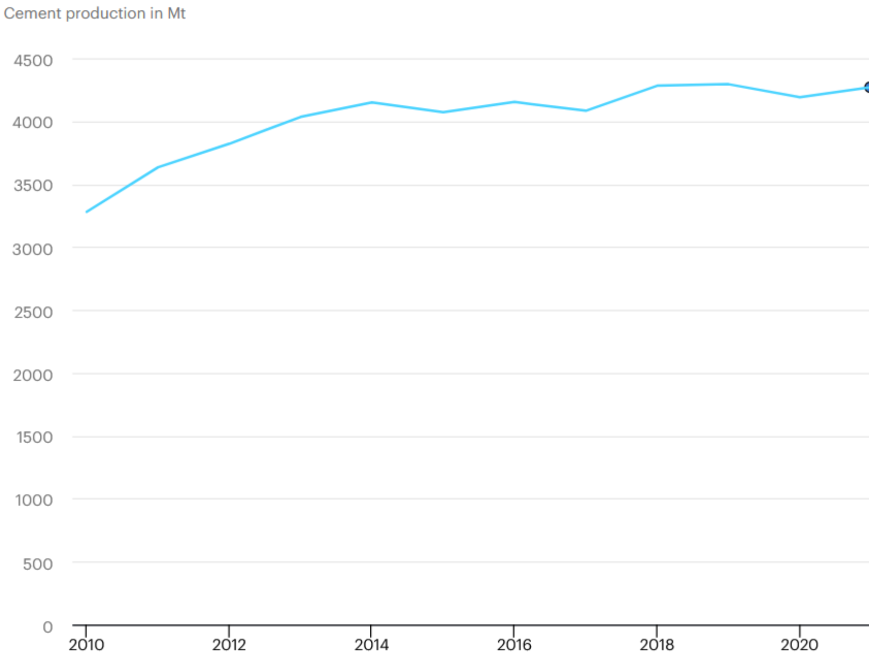

Figure 7 : World cement production 2010-2021.

Source: IEA, 2022a.

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[76] Cf. IEA, 2022a.

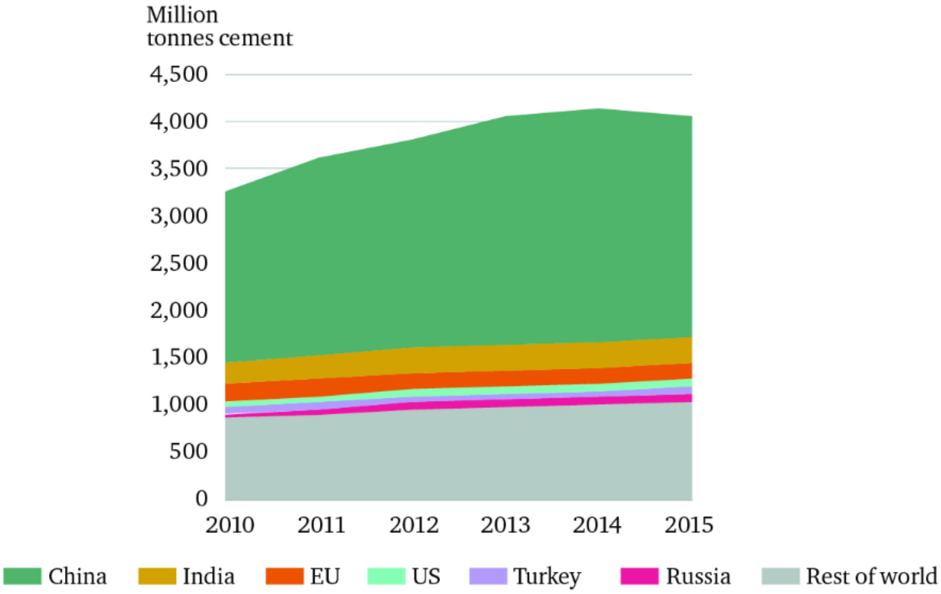

Figure 8 : Cement production and CO_2 emissions by country (2010-2015).

Source: CarbonBrief, 2018. [77]

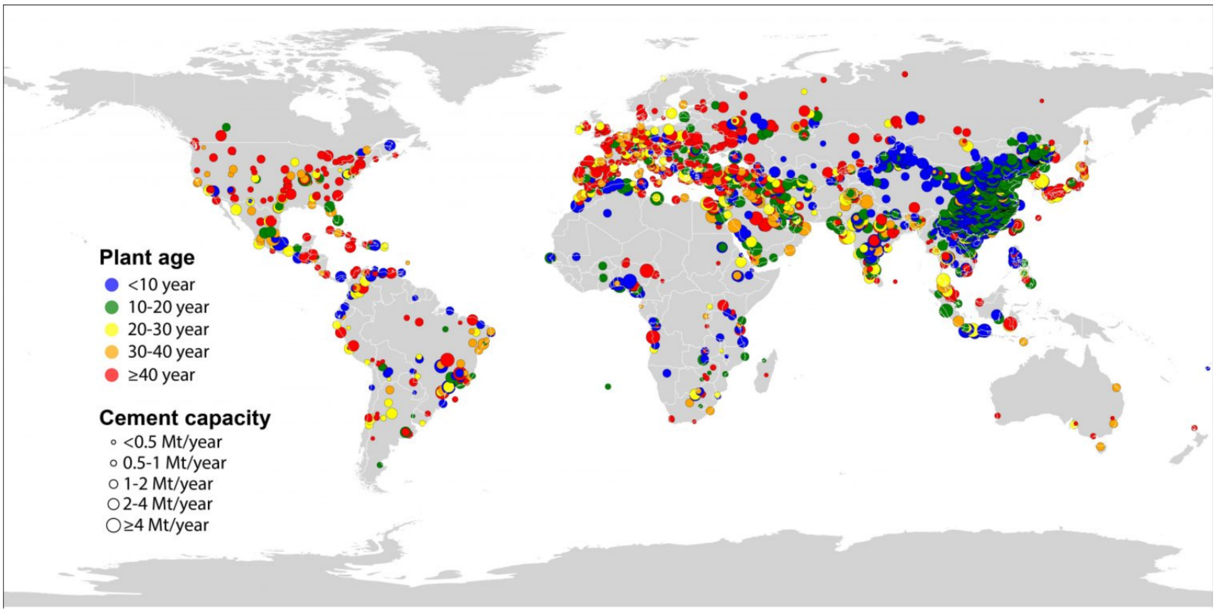

Figure 9 : Global cement production infrastructure in 2019.

Source: Global Infrastructure Emission Database, 2021.

In particular, the production of cement in India and other emerging economies could continue to increase. An increase of up to 25 % to over 5 Gt by 2050 is possible (Figure 10). The share of India, Africa and Pacific countries is increasing. However, the IEA's Net Zero Scenario assumes stagnating cement consumption of around 4.3 Gt until 2030. The reasons for this lie in higher construction and material efficiency, as well as the use of alternative building materials.

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[77] The presented CO_2 emissions only show the process-related emissions in cement production, but not the fuel-related emissions. The total emissions from cement production are higher by a factor of 2.

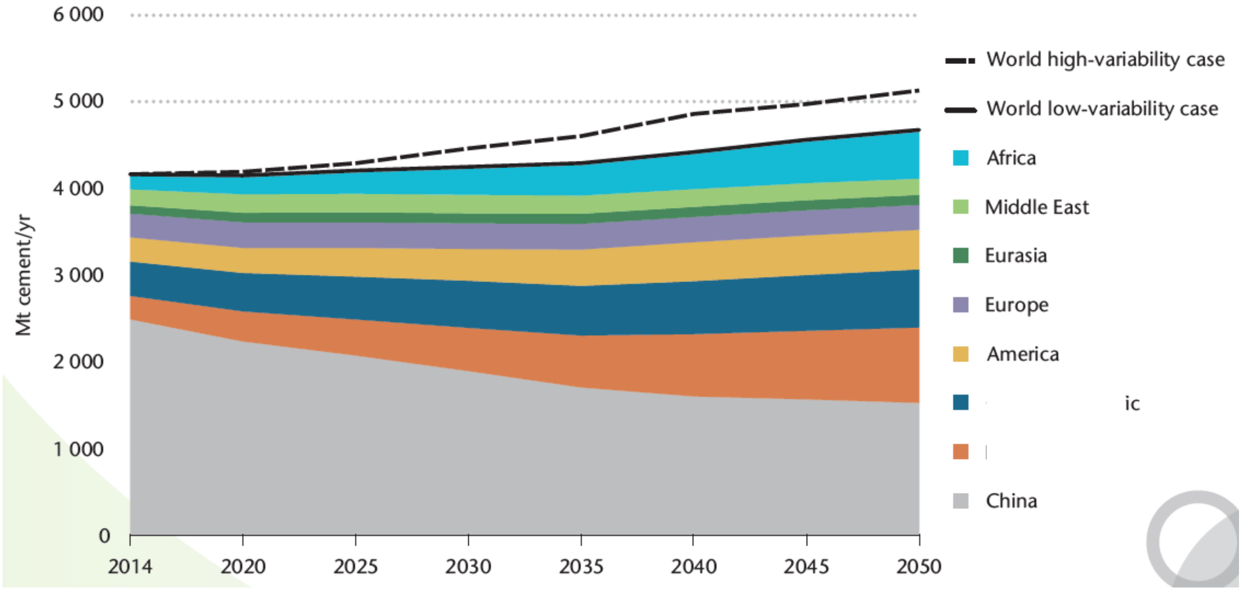

Figure 10 : Cement production 1990 to 2006 and forecast to 2050.

Source: IEA and Cement Sustainability Initiative, 2018.

Since 1990, CO_2 emissions from the cement industry have more than tripled, rising from 0.86 Gt to almost 2.9 Gt in 2021 (Figure 11). This corresponds to 6-8 % of global CO_2 emissions. Thus, cement production is one of the largest sources of greenhouse gas emissions. [78]

The production of one ton of cement results in CO_2 emissions of between 0.65 tons and 0.95 tons. Differences in efficiency among manufacturers, the use of different fuels, the type of cement produced or even the system limits in calculation lead to differences in the specific CO_2 intensity of cement production. The CO_2 intensity of cement production has decreased globally by 18 % since 1990,[79] in Germany even by 22 %.[80] Globally, however, the average CO_2 emissions per ton of cement are 20 % higher than in production with the best available technology.[81] This means that with today's available technology alone, an emission reduction in cement production of about one fifth would be possible.

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[78] If cement production were a country, it would be the third largest CO_2 emitter after China and the USA.
[79] Cf. Lehne & Preston, 2018.
[80] Cf. VDZ, 2022.
[81] Cf. CarbonBrief, 2018.

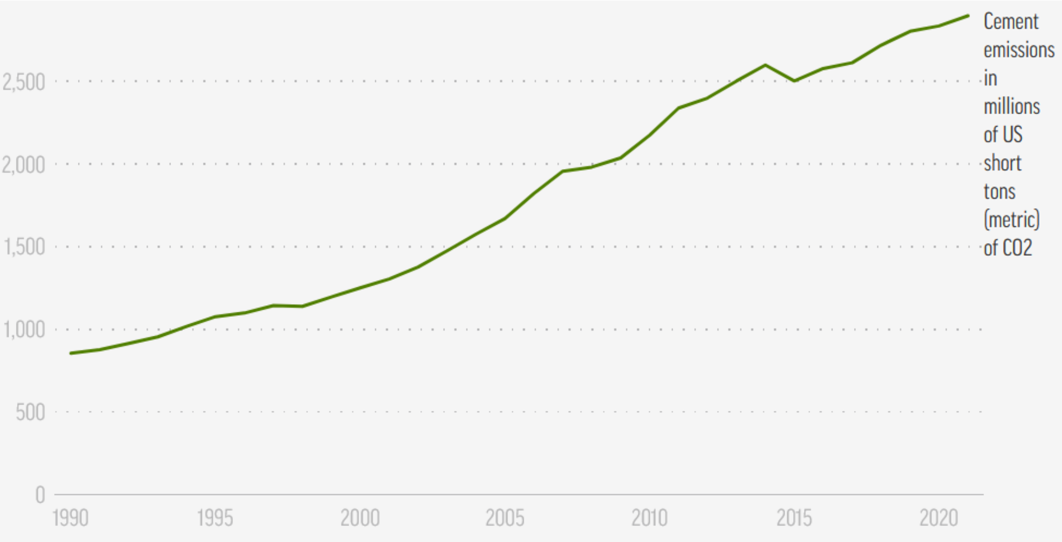


Figure 11 : Worldwide CO_2 emissions from cement production (energy- and process-related) in MST (Million Short Tons).

Source: Borenstein, 2022.

The most important energy and emission-related parameters of cement production are shown in Table 2 summarised.

Parameter	Values
emissions and energy consumption (promotion until furnace)	185 MJ/tonne cement 28 kg CO_2 /tonne cement
Emissions and energy consumption (calcination in the kiln)	3150 MJ/tonne cement Calcination: 479 kg CO_2 /tonne of cement (process-related) Fuels: 319 kgCO_2 /tonne cement (energy-related)
Emissions and energy consumption (cooler to transport end product)	560 MJ/tonne cement 99 kg CO_2 /tonne cement
Emission intensity of cement (2020)	650-950 kg CO_2 /tonne cement (depending on cement type and fuels)
Cement production (2021)	4,270 Mt
Total emissions (2021)	2,897 Mt

Table 2 : Energy and emission-related parameters of cement production.

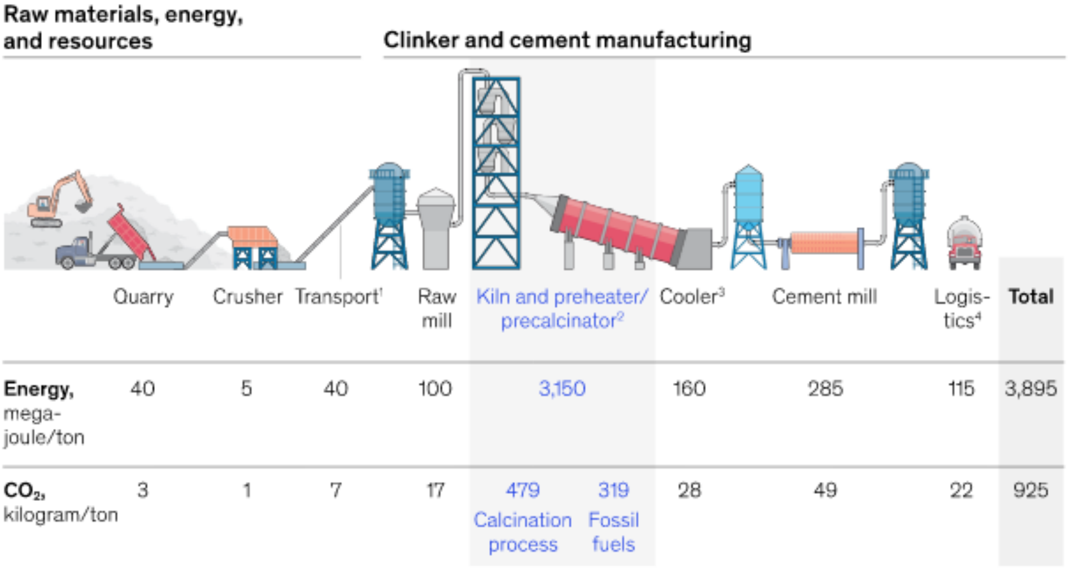
3.2.2.2 Sources of CO emissions$_2$

In principle, only the emissions directly related to cement/concrete production are considered (Scope 1). Indirect emissions (Scope 2, 3) such as logistics are only briefly touched upon but are not taken into account for the emission reduction strategies at this point.

The most important raw materials for cement are limestone, lime marl, chalk, as well as sand, gypsum, clay and various other aggregates. The raw materials are ground and then sintered into cement clinker. Clinker production is the most energy-intensive manufacturing step and is associated with the highest CO_2 emissions. In this step, the calcium carbonate of the limestone is converted into calcium oxide. Two processes are therefore the main causes of the high greenhouse gas emissions in the production of cement:

- Energy-related emissions from fuel consumption for the combustion process: 30-40 % of total emissions
- Process-related release of CO_2 during limestone deacidification: 50-60 % of total emissions (CaCO3 + heat → CaO + CO $)_2$

About 10 % of the emissions in the cement value chain come from the extraction, grinding and transport of materials. Along the value chain of the cement industry, there are different processes in which CO_2 emissions occur. Figure 12 shows the process steps and their specific energy requirements and emissions.



	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]	Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process 319 Fossil fuels	28	49	22	925

[1] Assumed with 1kWh/t/100m.
[2] Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3] Assumed reciprocating grate cooler with 5kWh/t clinker.
[4] Assumed lorry transportation for average 200km.

Figure 12 : Cement production process with specific energy consumption and CO_2 emissions of the individual process steps.

Source: McKinsey, 2020.

First, limestone is mined in quarries and then crushed. The raw material is then burned in rotary kilns at very high temperatures of around 1450 °C to form cement clinker. During this process, the chemical properties are formed that give the cement its performance and the subsequent concrete its high stability. During the burning process, process-related CO_2 emissions occur during the calcination of the limestone into quicklime, a preliminary stage of the cement clinker. Clinker is then ground into the final product with the addition of other aggregates such as granulated blast furnace slag, fly ash, limestone and gypsum. In order to obtain cement types with specific properties, granulated blastfurnace slag, fly ash, limestone and gypsum can be added in different doses and finenesses before grinding. The cement is then transported to the points of use. The high shares of the kiln and the calcination process in the energy consumption and CO_2 emissions are clear.

A further illustration of the CO_2 emissions in the cement value chain is shown in Figure 13 can be seen. In addition to the process steps in cement production and the resulting CO_2 emissions, possible solutions for reducing CO_2 emissions are also shown.

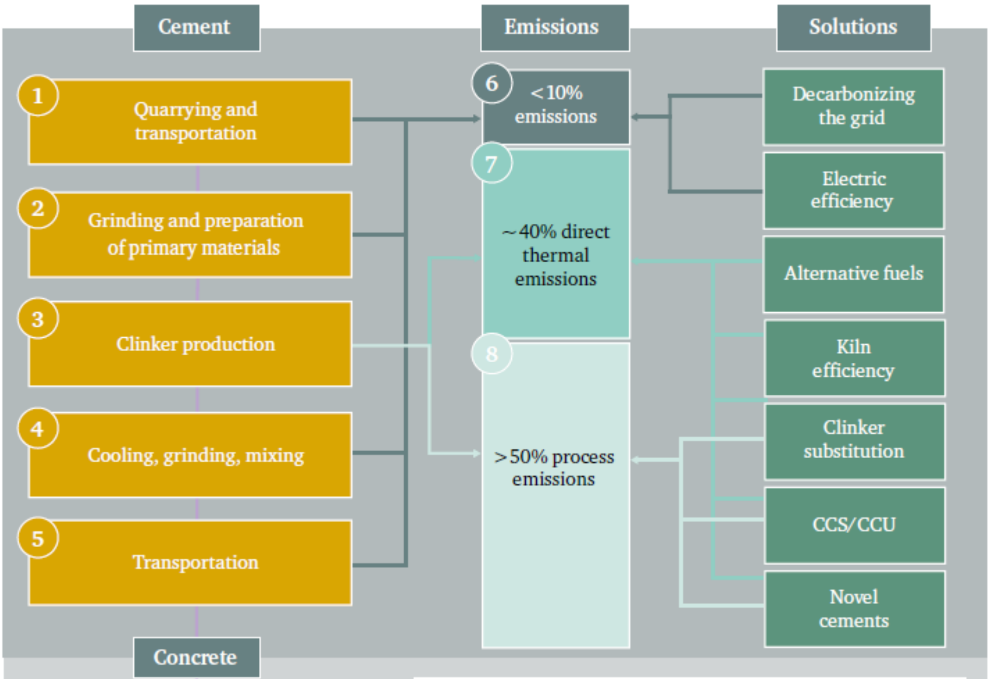


Figure 13 : Cement production steps, CO_2 emissions and possible solutions for CO_2 emission reduction.

Source: Lehne & Preston, 2018.

3.2.2.3 Technical options for CO2 reduction

The reduction of CO_2 emissions in the production of cement is of great importance for a climate-neutral energy system. The cement industry pursued five paths in particular:[82]

- Increased thermal and electrical efficiency in all process steps (degradation, transport, combustion, grinding)
- Use of alternative fuels (switching from fossil fuels such as coal to biomass or waste).
- Substitution of cement clinker with other materials (fly ash, limestone or granulated blast furnace slag)
- Carbon capture, storage and utilisation (CCUS) for process-related emissions

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[82] See Lehne & Preston, 2018; McKinsey, 2020; VDZ, 2022; Global Cement and Concrete Association, 2021.

- Development of new types of cement and concrete (replacement of clinker cement with low-carbon materials with similar properties)

Progress in the first three pathways has reduced CO_2 emissions from the global cement industry by 18 % since 1990, compared to no progress. The development of CCUS in the cement industry, as well as the development of substitutes for cement, is still in the development stage.

Thermal and electrical efficiency

The first lever to reduce emissions is to improve kilns and plants so that less energy is needed to produce cement. Changing the plant design, switching to higher efficiency dry kilns, upgrading motors and mills, and using variable speed drives can significantly reduce energy consumption and costs. Companies are increasingly using equipment to track and monitor operations, allowing them to make their production process more efficient. More efficient milling processes can lead to electricity savings, which has a positive impact on overall energy efficiency.[83] The use of renewable electricity for the electrical consumers also allows for emission reductions. Optimising the use of waste heat can also reduce the operating costs of cement plants by 10 to 15 %.[84]

Although the industry has invested heavily in optimising production processes, an efficiency gap remains. The production of cement according to the current best available technology (BAT) and practice results in a thermal energy consumption of around 2.9 GJ/ton of clinker. In comparison, the global average in 2014 was 3.5 GJ/ton of clinker, almost 20 % higher. The efficiency gap largely reflects the use of older plants in Europe and the US. Meanwhile, the Indian cement industry is one of the most energy-efficient in the world, with an average thermal energy consumption of around 3.0 GJ/ton of clinker.[85]

Use of alternative fuels

The second way to reduce emissions in cement production is to switch from fossil fuels to alternatives such as biomass and waste. In many cases, coal is the main fuel used, but cement kilns can also burn biomass and waste instead of fossil fuels, as the high processing temperature and the presence of limestone purify the gases released. However, the type of alternative fuel used depends on the local availability and quality of the alternatives. Often these are outside the direct control of the cement manufacturers. The use of alternative fuels in cement production in different regions is shown in Table 3.[86]

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[83] Cf. Lehne & Preston, 2018.
[84] Cf. IFC, 2014.
[85] Cf. Lehne & Preston, 2018.
[86] Cf. Lehne & Preston, 2018.

Region	Europe	North America	China, South Korea and Japan	India
Share of alternative fuels	43 %	15 %	8 %	3 %

Table 3 : Use of alternative fuels in cement production by region.

Source: Lehne & Preston, 2018.

Using alternative fuel, especially in emerging countries such as China and India, emissions can still be a strongly reduced. However, there is also room for improvement in Europe. An average cement plant could replace about 60 % of its fuel with alternatives. Some European manufacturers are already working with more than 90 % waste fuels for longer periods of time.[87]

Substitution of cement clinker with other materials

The amount of cement clinker used can also be reduced by substituting it with clinker substitutes such as fly ash, granulated blast furnace slag and limestone. How much clinker substitute can be added to the cement or concrete depends on the type of substitute and the desired concrete quality. Some substitutes - e.g. granulated blast furnace slag - theoretically allow substitution levels of over 70 %, which could reduce emissions during production by over 60 %.[88]

So far, clinker substitution has contributed to an average reduction of 20-30 % in CO_2 emissions per ton of cement compared to the 1980s. While the decline in clinker consumption was stronger in the 1990s, it has recently levelled off or even slightly increased again (Figure 14).[89]

In most regions, there is still considerable room for improvement, as shown by the target set in the 2018 Technology Roadmap: By 2050, an average clinker share of 0.60 should be achieved globally.[90] The main barriers to clinker substitution are usually cement quality, availability and cost of substitutes depending on the region, consumer acceptance, and standards and regulations.

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[87] Cf. Ecofys & Cembureau, 2016.
[88] Cf. Schuldyakov et al., 2016.
[89] Cf. Lehne & Preston, 2018.
[90] Cf. IEA and Cement Sustainability Initiative, 2018.

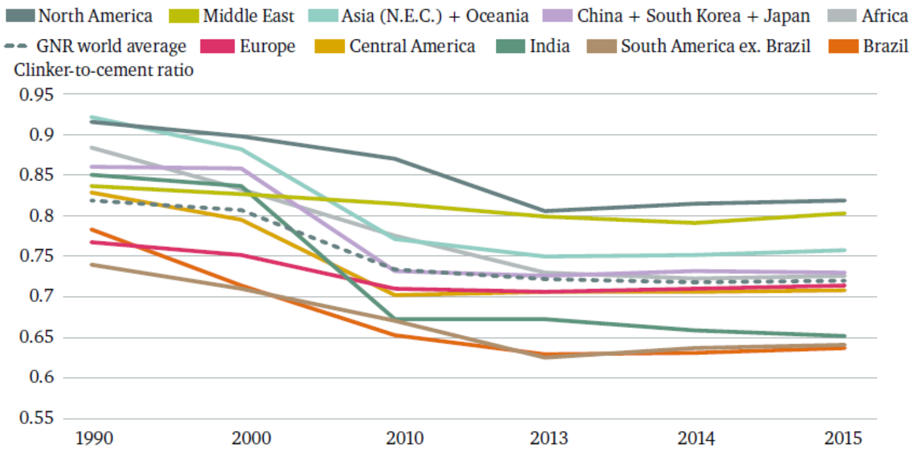

Figure 14 : Clinker-to-cement ratio in different regions (1990-2015).

Source: Lehne & Preston, 2018.

CCUS (see also chapter 2.8)

Since the process emissions from heating limestone for clinker production cannot be avoided by simply changing the fuel and improving energy efficiency, the application of CO capture technologies$_2$ is inevitable. Even with large-scale substitution of cement clinker, emissions from the portion of clinker that continues to be produced would be challenging. In general, for existing and older plants (cf. Figure 9), the focus is on end-of-pipe technologies such as CCS, as cost pressures do not allow for the development and construction of completely new types of plants. For the capture of CO_2 in cement production, costs of 40-70 USD/t CO_2 can be expected.[91]

The cement industry has participated in several projects to develop CCUS. However, as in other sectors, the development of CCUS up to 2020 has been slow. Most CCS technologies and applications are still at the basic research or demonstration stage (for a good compilation of CCS applications in cement production, see Plaza et. al). If pre-combustion CCS plants were used, only the capture of fuel emissions would be possible. However, since the capture of process-related emissions during calcination is also relevant, CCS processes such as post-combustion or oxyfuel are more promising. [92]

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[91] Cf. CCS Institute, 2021.

[92] Cf. Plaza et al., 2020.

Post-Combustion

Conventional kilns in existing and new cement plants can be retrofitted with post-combustion CO_2 capture technologies without significantly changing the cement production process. Only the energy management strategies and the start-up and shut-down procedures would be affected. The fact that many plants still have a few years of lifetime ahead of them (expected lifetime 30-50 years) reinforces the potential of post-combustion capture technologies, especially in emerging and developing countries with plants of low age. Various technologies can be used to capture the furnace gas. In particular, chemical absorption by amine scrubbing (Figure 15), membranes and sorption on solids are used in demonstration plants. [93]

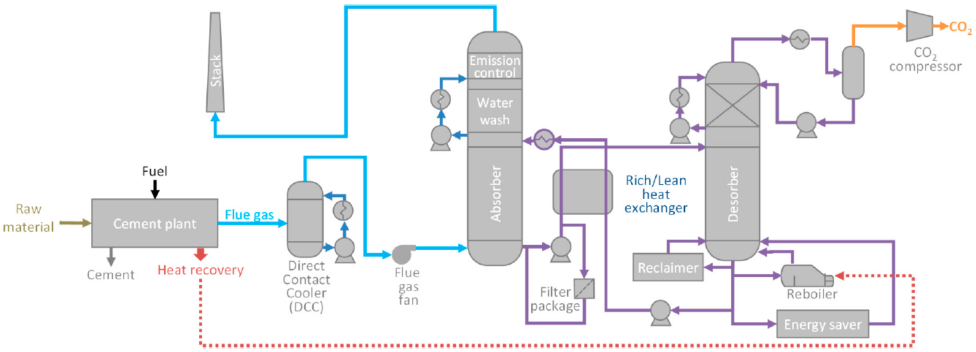

Figure 15 : Schematic of a cement plant with separation process of CO_2 with amine scrubbing.

Source: Plaza et al., 2020.

Oxyfuel process (see also chapter 2.8)

In the oxyfuel process, pure oxygen is used instead of air for the combustion process. As a result, a large proportion of the exhaust gas consists of CO_2, which can then be separated more easily (Figure 16). Oxyfuel combustion improves fuel efficiency but requires new construction and redesign of the cement plant to minimise air intake and optimise the heat recovery system. The main economic and energy disadvantages arise from the need for an air separation unit and the need to develop new kilns adapted to the conditions of oxyfuel combustion.[94]

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[93] Cf. Plaza et al., 2020.
[94] Cf. Plaza et al., 2020.

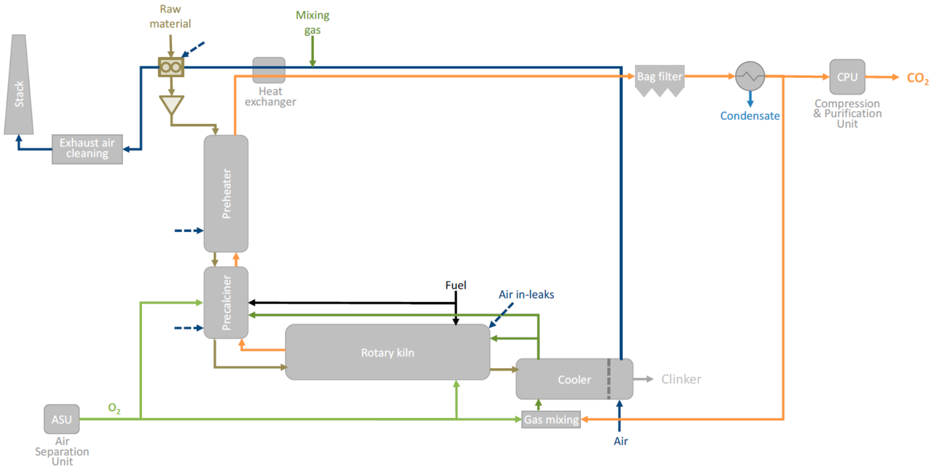

Figure 16 : Schematic of a cement plant with oxyfuel process for CO capture. $_2$

Source: Plaza et al., 2020.

Calcium looping

Calcium (CaL) looping is one of the most promising CO_2 capture technologies for the cement sector. CaL is based on reversible carbonation in two interconnected reactors: a carbonator and a calciner. This uses a reaction that takes place at medium temperatures between lime (CaO) and CO_2 to form limestone (CaCO3). At higher temperatures, the reaction can be reversed to release pure CO_2. In the carbonator, CaO is brought into contact with the CO_2 -containing flue gas at 600-700 °C. The CaCO3 that is formed is then converted into limestone. The $CaCO_3$ formed is then fed into the calcination reactor, where it is heated to 890-930 °C to recover the CO_2. The separated CO_2 is then purified and can be transported further in concentrated form. The regenerated CaO is returned to the carbonator reactor.[95]

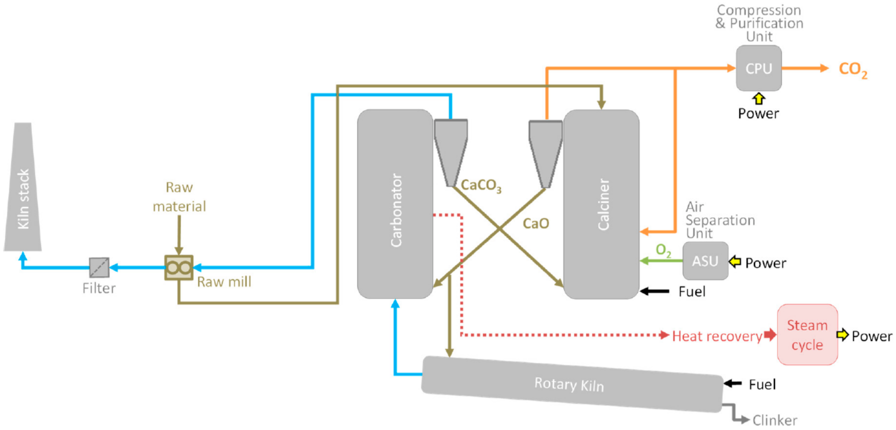

Figure 17: Schematic of the calcium loop.

Source: Plaza et al., 2020.

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[95] See Plaza et al., 2020; Fransson & Detert, 2014.

Direct deposition

Direct capture offers another possibility for separating CO_2 emissions in cement production. In this process, a conventional calciner is redesigned in such a way that the limestone is heated indirectly (Figure 18). The direct separation reactor, in principle a special steel tube, acts as a large heat exchanger. In this way, the process emissions generated during the calcination of limestone do not come into contact with the emissions from the fuel combustion. The latter could also be captured with other CCS technologies. The main advantage of the technology is the low energy input, which is only related to heat losses. On the other hand, the main challenge is the necessary high temperature for calcining limestone.[96]

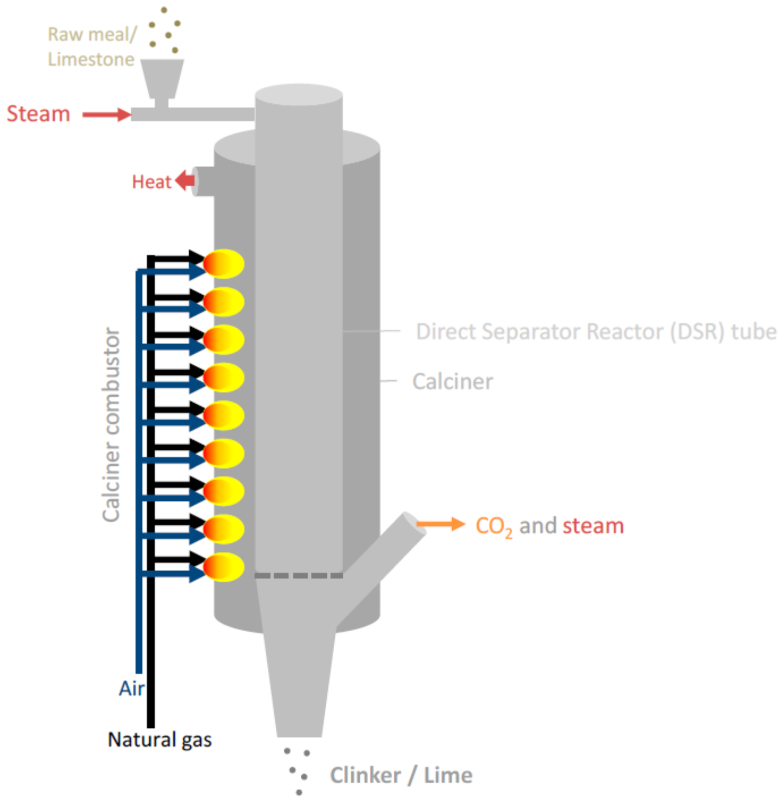

Figure 18 : Schematic of direct deposition (LEILAC).

Source: Plaza et al., 2020.

The main obstacles to the large-scale application of CCS have so far been the higher costs of capturing CO_2 (40-90 USD/t CO).₂[97] However, the application of CCS in the cement industry can be stimulated by pricing emissions accordingly. The lack of or inadequate legal framework for CO_2 storage in some countries is also a challenge.[98] Many cement plants are also too small to justify building the necessary transport infrastructure for captured CO_2 alone.[99] This is not a problem if bundling with

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[96] Cf. Plaza et al., 2020.
[97] Cf. Plaza et al., 2020.
[98] Cf. Lehne & Preston, 2018.
[99] Cf. Global CCS Institute, 2016.

other industrial CO_2 sources is possible. Often, however, cement production plants may not be located at a suitable site. The CO_2 produced could then be used locally for CCU, for example in the production of synthetic fuels (see also application example in 3.2.2.4).

Development of new types of cement and concrete

Novel types of cement and concrete can also reduce overall emissions in the production process. Low-carbon or novel cements are materials that are made from alternatives to cement clinker, release less energy and emissions in production, and still have the conventional cement properties. By changing the raw materials used (in most cases, the proportion of limestone is reduced), these clinkers can reduce process emissions from limestone calcination and emissions from fuel combustion.[100]

For example, carbonisable calcium silicate clinker (CCSC), as used in concrete by the company Solidia, can reduce process emissions by 43 %.[101] KIT has also taken a similar development direction with celitement. The binder is produced at temperatures of only 150 to 300 °C. However, celitement is not yet a fully developed product. However, celitement is not yet a standardised building material.[102]

Magnesium oxides (MOMS) derived from magnesium silicates could also theoretically be produced from materials that do not contain carbon. This technology was developed by the company Novacem but has so far not been able to demonstrate any resounding success. The relevant knowledge and patents were acquired by the technology and industry group Calix in 2012.[103]

Geopolymer or alkali-activated binders can also have an 80-90 % lower footprint than normal Portland cement. Both CCSC and MOMS can be hardened by carbonation (using CO_2 instead of water). This means that they could absorb and contain more CO_2 than is emitted during production. This would make these types of cement "carbon-negative".[104] Another way to save emissions in the cement and concrete industry is to use recycled concrete. Demolition concrete from buildings can help to both reduce the production of new cement and reduce the burning temperatures to only 1000 °C. [105]Figure 19 shows the process emissions of alternative clinker compared with Portland clinker.

However, these new types of cements and concretes have not yet been able to achieve large market shares. Quality problems with new types of cements and mixes prevent higher market penetration. Many of the new products meet with consumer resistance, as almost all standards, regulations and protocols for testing cement binders and concrete are based on the use of Portland cement. This

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[100] Cf. Lehne & Preston, 2018.
[101] Cf. Solidia, 2022.
[102] Cf. Celitement, 2022.
[103] Cf. Majcher, 2015.
[104] Cf. Zajac et al., 2022; Lehne & Preston, 2018.
[105] Cf. KIT, 2022.

makes handling and experimentation with the novel products difficult. Not all of these novel binder technologies have reached a level of maturity to be used on a large scale. Finally, there is also resistance and difficulties to expand the stakeholders beyond the producers of novel cements and concretes.[106]

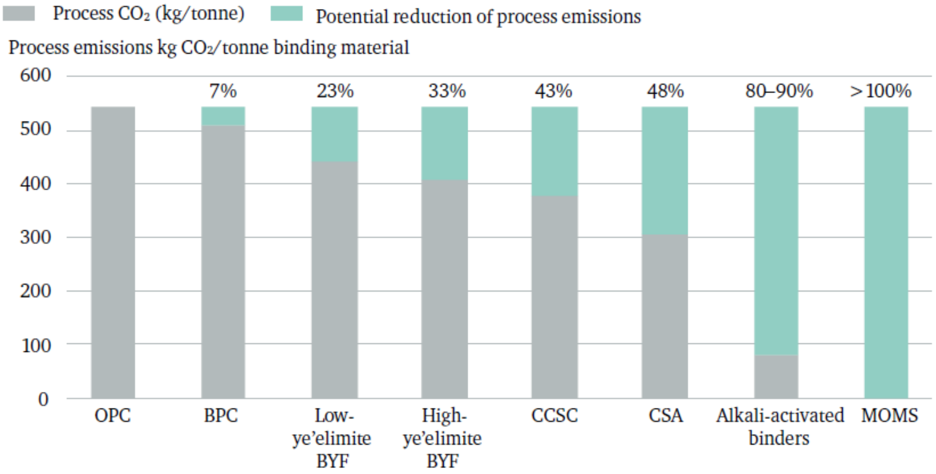

Figure 19 : Process emissions of alternative clinkers compared with Portland clinker (OPC: Ordinary Portland Clinker, BPC: Belite-rich Portland Clinker, BYF: belite ye'elimite-ferrite, CCSC: Carbonatable Calcium Silicate Clinkers, CSA: Calcium Sulphoaluminate Clinker, MOMS: Magnesium Oxides derived from Magnesium Silicates).

Source: Lehne & Preston, 2018.

Substitution of concrete and planning of structures

There is also leverage in the design and construction of buildings that should not be underestimated to limit the use of cement per se. These levers can be implemented with the current standards and regulations. The reduction of CO_2 emissions in the construction of a building must become an important design parameter, along with quality, cost and speed. Designers of buildings and infrastructures can save CO_2 emissions by choosing the geometry and system of the floor, the spacing of support columns and optimising concrete strength and element size. This can be achieved while maintaining all the performance benefits of concrete construction.[107] Also possible is the substitution of cement with other less CO_2 intensive building materials, such as clay, wood or other composites.[108]

Net Zero path of the cement industry

The reduction and possibly complete avoidance of CO_2 emissions in the production of cement requires an interplay of all the possibilities described above. Figure 20 shows the net zero path of the

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[106] Cf. Lehne & Preston, 2018; Rose, 2022.
[107] Cf. Global Cement and Concrete Association, 2021.
[108] Cf. McKinsey, 2020.

Global Cement and Concrete Association (GCCA) with different possibilities of emission reduction and their shares in the overall path.

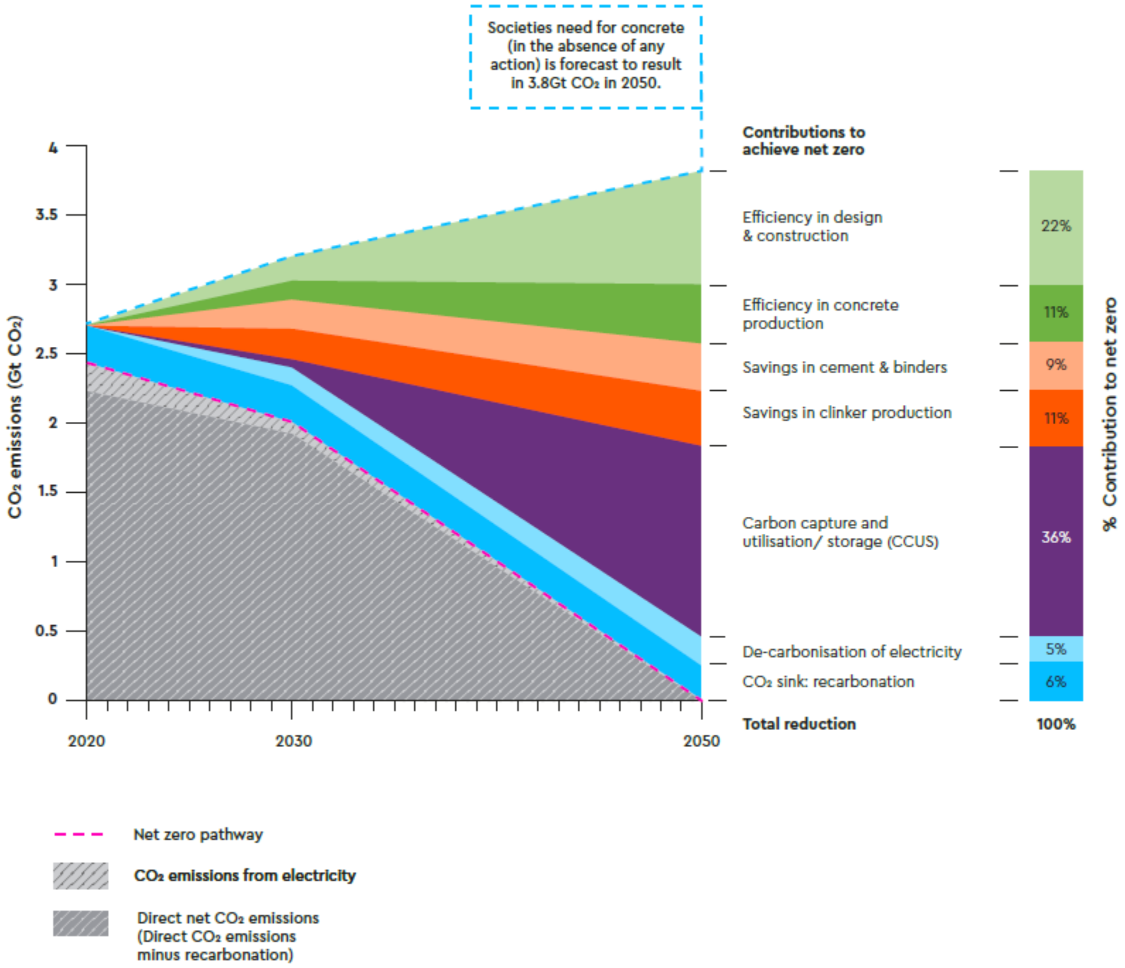

Figure 20 : Net Zero pathway for the cement and concrete industry.

Source: Global Cement and Concrete Association, 2021.

The reduction of emissions in the production and use of cement should together account for 20 % of the total reduction. Increased efficiency in mixing concrete and also more economical use in structures through changed design itself are expected to reduce up to 33 % of emissions. 11 % of the emission reduction comes from decarbonised electricity supply and the storage of CO_2 in concrete (recarbonisation). These measures are expected to have an increased impact already by 2030, while CCUS will be scaled up to the necessary Gt scale mainly from 2030 onwards. The use of CCUS in the cement industry is mainly necessary for process-related emissions and is expected to account for 36 % of the total savings according to the Net Zero pathway.

3.2.2.4 Application example Schwenk cement

At the SCHWENK Zement site in Mergelstetten in Baden-Württemberg/Germany, four cement manufacturers Buzzi Unicem SpA - Dyckerhoff GmbH, HeidelbergCement AG, SCHWENK Zement

GmbH & Co. KG, and Vicat S.A are working together under a newly founded research company "Cement Innovation for Climate", CI4C for short. A demonstration plant on a semi-industrial scale is to be built there and put into operation at the beginning of 2024. Process-related CO_2 in cement production in Mergelstetten is then to be captured by an oxyfuel process (Figure 21).

Figure 21 : Illustration of the oxyfuel plant for the "catch4climate" demonstration project in Mergelstetten.

Source: HeidelbergCement, 2022.

A new kiln plant is needed for the new clinker production process. The "polysius pure oxyfuel" kiln plant is being realised by thyssenkrupp. Instead of ambient air with 21 % oxygen content, the new plant uses pure oxygen in the combustion process (oxyfuel). This increases the proportion of CO_2 in the process-related exhaust gases from 25-30 % to almost 100 %.[109] High-purity CO_2 can be separated in this process. The project partners plan to invest 130 million euros.[110]

The medium-term goal of the "catch4climate" project is the subsequent use of the captured CO_2 as a raw material for the production of climate-neutral synthetic fuels using renewable electricity and green hydrogen directly at the site. This also eliminates the need to transport the CO_2. Since the cement production plant is located in the south of Germany, the CO_2 would first have to be transported there for injection in northern Germany or Norway. The cost of building a CO_2 pipeline for the captured emissions from the cement plant would be too expensive due to the insufficient quantity. Transport by truck would also not be feasible for logistical and cost reasons. The partner for the production of the fuel is SkyNRG and Stuttgart Airport. From 2028, the climate-neutral kerosene will then also be used on an industrial scale (50,000 tonnes/year) at Stuttgart Airport. [111]

SCHWENK Zement will invest over EUR 330 million for the two plants (oxyfuel separation and synthetic fuel production). [112]

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[109] Cf. HeidelbergCement, 2022.
[110] Cf. Heidenheimer Zeitung, 2022.
[111] Cf. Heidenheimer Zeitung, 2022.
[112] Cf. SWR, 2022.

3.2.2.5 Developmental relevance

Only just under 10 % of global cement production takes place in the US or the EU. Many cement production plants are located in emerging and developing countries and also have a lower average age (compare Figure 9). At the same time, the projected demand for cement and concrete will also increase, especially in those countries that have not yet developed any or very little infrastructure. A large part of the decarbonisation in the cement industry must therefore take place in the emerging and developing countries. The methods developed in the industrialised countries, but also in China and India, for saving energy and emissions in cement production must be applied and greatly expanded worldwide. However, the realisation of CO_2 saving measures in the cement industry is accompanied by considerable additional costs - here, a mechanism for financial compensation must be created for the developing and emerging countries.

For example, the IEA estimates that achieving the 2-degree target by 2050 will require additional expenditure for the cement industry of USD 283 to 361 billion compared to the case where no further action would be taken (IEA (2018): Technology Roadmap Low-Carbon Transition in the Cement Industry).

In Figure 22 shows the cumulative investment needs of the cement industry until 2050 in three different scenarios. If, compared to the "no action" scenario, today's energy consumption trends as well as countries' commitments to limit CO_2 emissions according to the Paris Agreement were taken into account, this would result in additional financial requirements of 107 to 127 billion USD. This RTS, described as the baseline scenario, resulted in an estimated temperature increase of 2.7 degrees Celsius by 2100.

If we wanted to limit global warming to 2 degrees Celsius (2DS), global investment would increase by a further $176 billion to $244 billion.

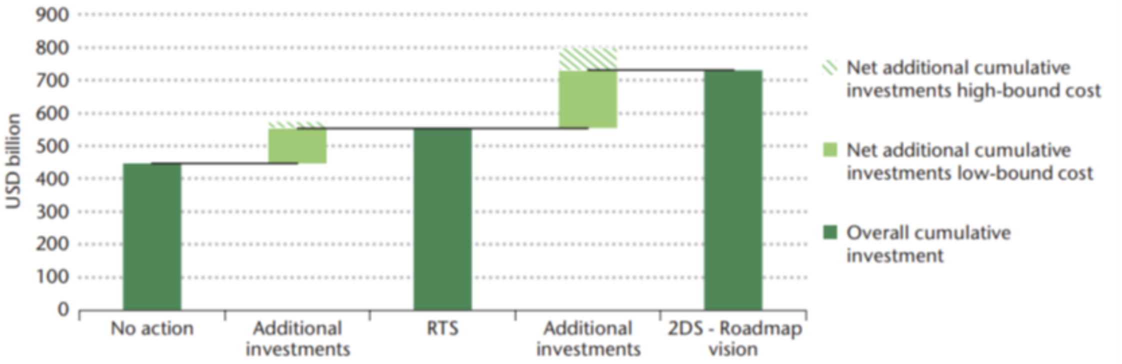

Figure 22 : Total cumulative investment needs by scenario until 2050.

Source: IEA (2018): Technology Roadmap Low-Carbon Transition in the Cement Industry

To realise this global additional investment need, a major effort is required at the political and private sector level as well as in the context of development cooperation. Governments, in collaboration with industry, need to find ways to leverage private investment in CO_2 mitigation measures that are unlikely to occur without incentives. For example, through sustainable financing and supportive risk mitigation mechanisms, they should ensure that the development and demonstration of new technologies and processes that demonstrate the potential to reduce CO_2 emissions are encouraged. All stakeholders should intensify cooperation to improve the implementation of state-of-the-art technologies and share best operating practices.

It is also of central importance to intensify all efforts to develop and introduce effective international CO_2 -pricing models. Among other things, this must ensure that local cement production with lower CO_2 emissions remains competitive with cement imports with higher CO_2 emissions and that previously made investments can be refinanced. Furthermore, governments should ensure that regulations and standards are in place to allow greater use of alternative binders for cements in order to reduce the clinker content of cement and concrete while maintaining product quality. Finally, development cooperation has a major role to play in terms of knowledge exchange and know-how transfer in the following areas, among others:

- Promoting technical exchange between countries and producers
- Development of feasibility studies and decarbonisation roadmaps
- Support for demonstration and application examples for emission reduction
- Financing measures to increase energy efficiency and reduce emissions

3.2.3 Chemistry

3.2.3.1 Presentation of global production volumes and emissions

The global chemical industry is characterised by great heterogeneity and complexity with regard to the products, methods and processes manufactured as well as the raw materials and energy sources used. This chapter cannot therefore provide a comprehensive analysis of the decarbonisation potential in the chemical industry, but it can provide an overview of the most important topics and paths to a climate-neutral chemical industry. A segmentation of the global chemical industry is shown in Figure 23 and illustrates the complexity of the value chain. The value chain of the chemical industry ranges from the extraction of the necessary raw materials for the production of basic chemicals to the production of industrial and consumer products and the waste disposal of these substances. In the following, the production of basic chemicals is of particular relevance, as this is where the greatest energy input and most emissions occur.

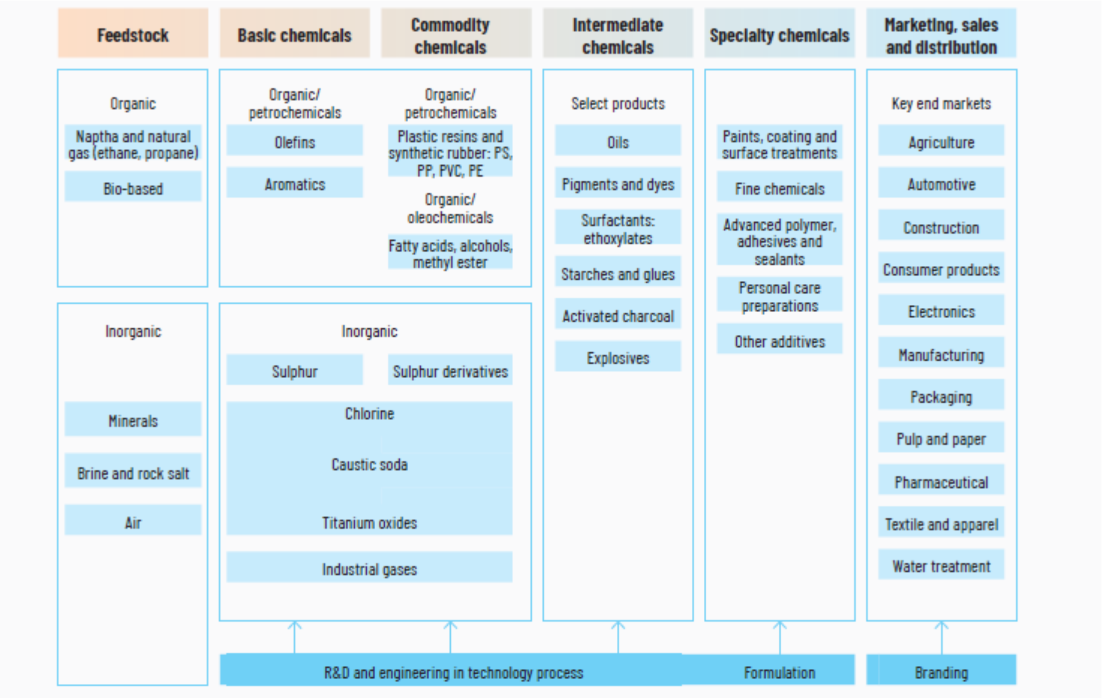

Figure 23 : Segmentation of the global value chain of the chemical industry.

Source: UNEP, 2019.

The production of chemicals has almost doubled since 2000, rising to almost 2,300 Mt by 2017, as shown in Figure 24 shows. The largest growth market during this period was China, with an annual growth rate of 11.8 %. However, the Middle East and India also showed rapid development, with annual growth of around 8 % each. [113]

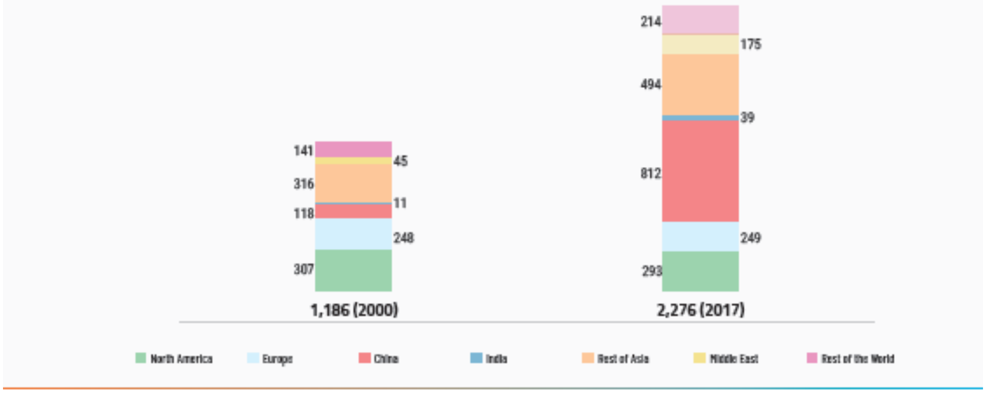

Figure 24 : Production capacity of the global chemical industry.

Source: UNEP, 2019.

The shift of value creation, production and sales from North America and Europe to China and other emerging Asian countries is unmistakable. A growing market is also forecast for the future. Especially the demand for important basic chemicals - starting products for many other substances - i.e. ammonia, ethylene, propylene, methanol, urea as well as BTX (benzene, toluene, xylene), will

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[113] Cf. UNEP, 2019.

increase by about 50-100 % by 2050.[114] This is also shown by the scenarios of the International Energy Agency for 2030 and 2050 (Figure 25).

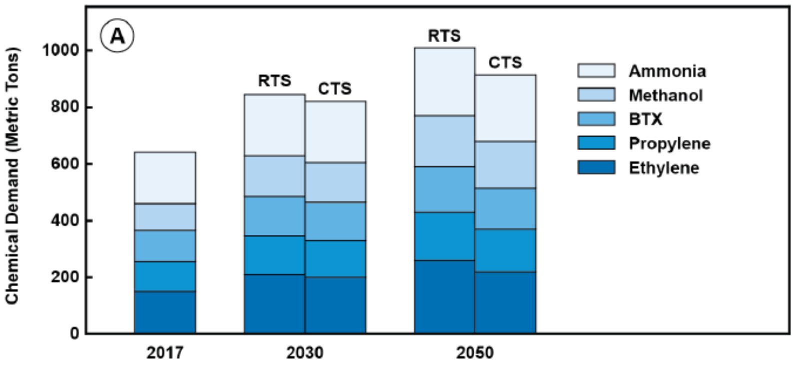

Figure 25 : Demand for key commodity chemicals in different scenarios (RTS: Reference Technology Scenario, CTS: Clean Technology Scenario).

Source: Mallapragada et al., 2022.

Greenhouse gas (GHG) emissions from the global chemical industry are reported in the literature to be between 1.6 - 3.3 Gt CO_2 -eq, depending on the system boundary.[115] Thus, the chemical industry is responsible for 3-6 % of global GHG emissions, similar to the steel and cement industries.

Estimates for future GHG emissions from the global chemical industry are highly dependent on assumptions about emissions abatement, energy efficiency and the use of other energy sources. An increase in emissions by 50-340 %, i.e. in the extreme case to almost 8 Gt under a business-as-usual scenario by 2050, shows that the decarbonisation of the global chemical industry has a very important role to play for a climate-neutral economy.[116]

3.2.3.2 Sources of CO emissions$_2$

About one third of GHG emissions in the chemical industry are process-related, the rest come from the energetic use of fossil raw materials to generate heat or electricity.[117] Likewise, raw materials such as gas or oil are also used directly as raw materials for other products. Figure 26 shows a detailed presentation of energy consumption and the resulting GHG emissions by application in the chemical industry.

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[114] Cf. Mallapragada et al., 2022; University of Tokyo, Center for Global Commons and Systemiq, 2022; Saygin & Gielen, 2021.

[115] Cf. McKinsey&Company, 2018; Gonzalez-Garay et al, 2021; Saygin & Gielen, 2021; Eryazici et al, 2021.

[116] Cf. Saygin & Gielen, 2021; Mallapragada et al., 2022; University of Tokyo, Center for Global Commons and Systemiq, 2022.

[117] Cf. McKinsey&Company, 2018; Saygin & Gielen, 2021.

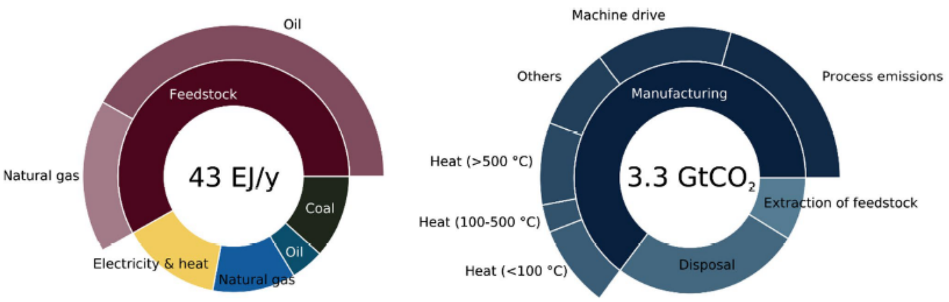

Figure 26 : Energy consumption and emissions of the chemical industry in 2015.

Source: Gonzalez-Garay et al., 2021.

Equally illuminating is the presentation of emissions by product stage in Figure 27. The high share of raw material use and basic chemicals in total emissions is clear.

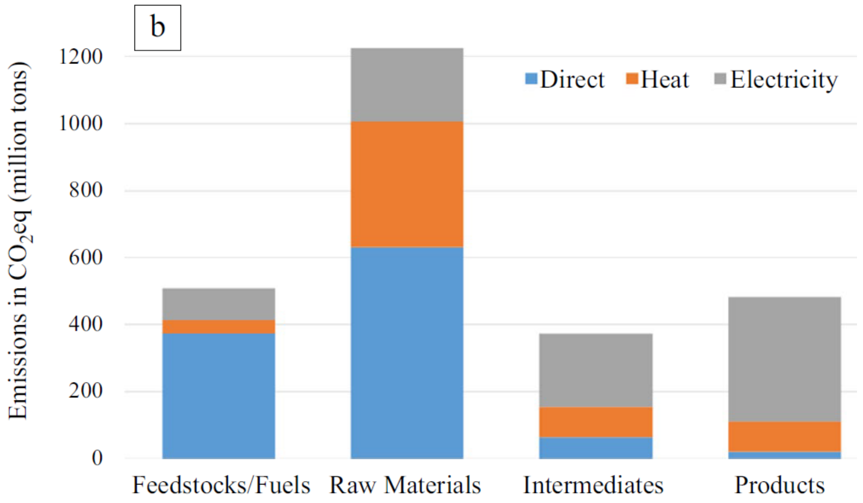

Figure 27 : GHG emissions in the value chain of the chemical industry.

Source: Eryazici et al., 2021.

Globally, 35 % of all GHG emissions from the chemical industry come from electricity consumption across the entire value chain. This value varies depending on the country and energy mix. Emissions from the combustion of fossil fuels for the generation of process heat account for 23 % of emissions. Most of this is from the feedstock production of ammonia, methanol and olefins, which are all high-temperature processes. Direct emissions in the value chain are responsible for 42 % of total emissions. Most direct emissions - about one third of total GHG emissions - occur either in feedstock production or in the extraction and refining of feedstocks and fuels. Other direct GHG emissions from raw materials come mainly from escaping and flaring methane gas from extraction processes, which could be reduced through global regulations and commitments by oil and gas companies.[118]

Particularly relevant GHG sources and energy consumers are the manufacturing processes of basic chemicals such as ammonia, ethylene, propylene, methanol, urea as well as BTX (cf. Figure 28 and

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[118] Cf. Eryazici et al., 2021.

Figure 29). These chemicals are the most produced worldwide and account for more than half of the total emissions of the chemical industry. An analysis on the chemical industry in the EU also concludes that only eight basic chemicals are responsible for 75 % of sectoral GHG emissions.[119]

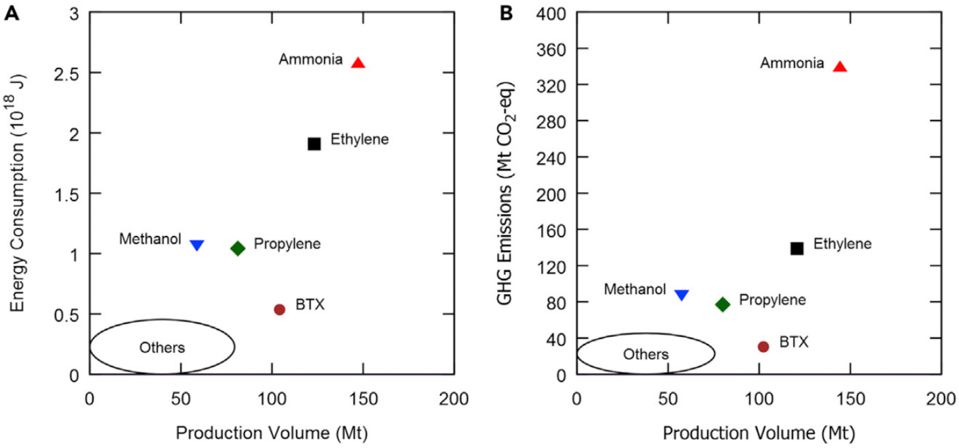

Figure 28 : Energy consumption and GHG emissions of the five most produced chemicals in 2010.

Source: Schiffer & Manthiram, 2017.

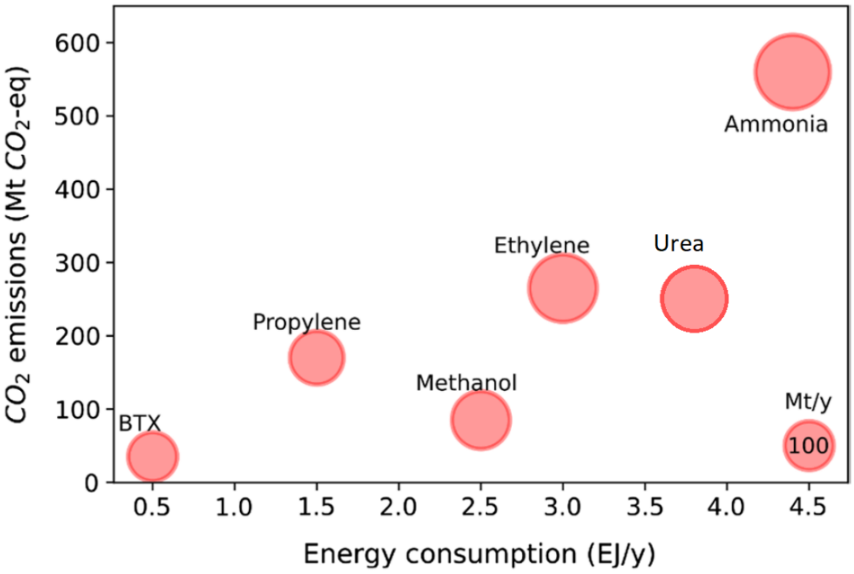

Figure 29 : Energy consumption and GHG emissions of the six most produced chemicals in 2018.

Source: Gonzalez-Garay et al., 2021; data on urea/urea inserted by author, based on S&P Global, 2022; Menegat et al., 2022; Baboo, 2015, DownToEarth, 2019).

Comparing the two graphs, the increase in production volume as well as GHG emissions between 50 - 100 % for the different chemicals within the period 2010-2018 becomes clear.

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[119] Cf. Accenture and NexantECA, 2022.

3.2.3.3 Technical options for CO_2 reduction

Despite the high complexity of production processes in the chemical industry, a framework for technical mitigation pathways can be developed based on the above source consideration of GHG emissions. Of particular importance are: the use of non-fossil carbon sources, the use of non-fossil energy sources in production and the capture of emissions that remain unavoidable (Figure 30). The approaches are complementary and can support each other.

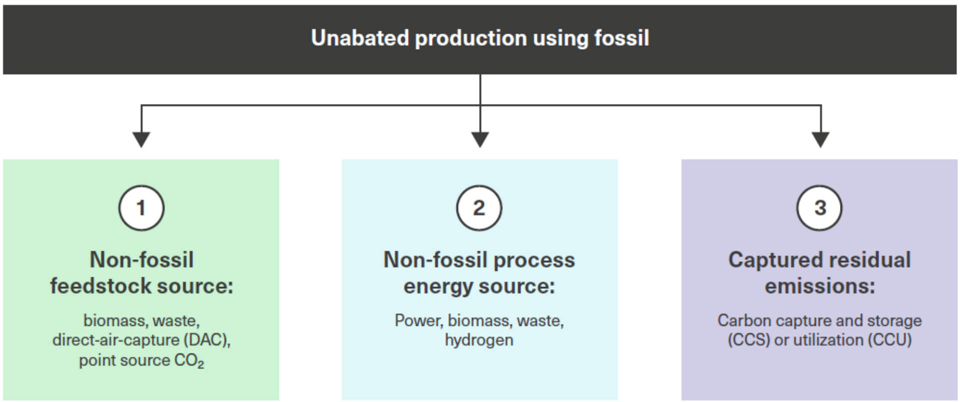

Figure 30 : GHG emission reduction pathways in the chemical industry .

Source: University of Tokyo, Center for Global Commons and Systemiq, 2022.

The following five topics play the most important role in reducing GHG emissions in the chemical industry:[120]

- Improved efficiency and electrification of processes
- Use of renewable or CO_2 -free electricity to reduce emissions from electrical consumers
- Use of CO_2 -free hydrogen as a basic raw material
- Use of non-fossil carbon sources
- Carbon capture, storage and utilisation (CCUS)

Improved efficiency and electrification of processes

Increasing energy efficiency in all processes in the chemical industry, especially through heat recovery, new catalysts, process innovations and better process and plant control can make a major contribution to reducing emissions. Similarly, the electrification of certain processes as well as heat generation can help to use less fossil fuels (e.g. through industrial heat pumps). Improving separation and recycling processes can also greatly improve resource and energy efficiency and contribute

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[120] Cf. Eryazici et al, 2021; Gonzalez-Garay et al, 2021; Saygin & Gielen, 2021; WEF and Accenture, 2022; A.SPIRE, 2021; University of Tokyo, Center for Global Commons and Systemiq, 2022; Vooradi et al, 2019.

to GHG reduction (e.g. recycling waste such as plastics, used oils or solvents as raw materials and carbon sources).

Use of renewable or CO_2 -free electricity to reduce emissions from electrical consumers

The use of CO_2 -free electricity is particularly important for reducing emissions from electrical consumers. The use of renewable or CO_2 -free electricity in combination with electrification has a great leverage effect. However, the availability of CO_2 -free electricity is not only an issue for the chemical industry but is equally necessary for mitigation in many other sectors.

Use of CO_2 -free hydrogen as a basic raw material

CO_2 -free hydrogen is very important for the reduction of GHG emissions in the chemical industry. In the chemical industry, hydrogen is mainly used as a raw material for the production of ammonia. As shown in Figure 28 and Figure 29 the production of ammonia is the largest singular GHG source in the chemical industry. The substitution of this often grey hydrogen from steam reforming of natural gas with green (renewably produced) or blue (capture of CO_2 during steam reforming) hydrogen therefore has high reduction potential. The use of CO_2 -free hydrogen also promises the possibility of high CO_2 savings for other processes in the chemical industry.

Use of non-fossil carbon sources

Carbon, as a chemical element, is a crucial building block of countless chemical components and the basis of all organic chemistry. To decouple chemical production from the exploitation of fossil resources and reduce GHG emissions, the use of "sustainable carbon sources" in the chemical sector must be increased. These carbon sources include CO_2 (and CO) captured from industrial wastewater, (fossil) waste streams (e.g. plastic waste) and biomass (waste). The use of biomethane instead of natural gas for certain processes can also play a role here. In combination with CO capture$_2$, the chemical industry could become a carbon sink.

Carbon capture, storage and utilisation (CCUS)

Especially for direct GHG emissions from processes, only the capture, use or final storage of CO_2 (CCUS) allows a reduction of GHG emissions. By capturing CO_2 from industrial processes and using the carbon as a raw material for further products, there is great potential for a sustainable carbon cycle in the chemical industry.

The different options for CO_2 reduction presented above must be combined in the implementation both in a plant and across the supply chain in order to largely eliminate GHG emissions from the chemical industry. For example, the generation of renewable electricity in combination with the production of hydrogen plays an important role in many of the processes. Likewise, the raw material that is further converted in processes to basic chemicals such as ammonia, methanol, ethanol or olefins can come from biomass, waste or even as recycled CO_2. The application of CCUS is also an integral part of a complete GHG emission reduction. Figure 31 shows an overview of the production processes for the manufacture of the most important basic chemicals in a largely GHG emission-free chemical industry.

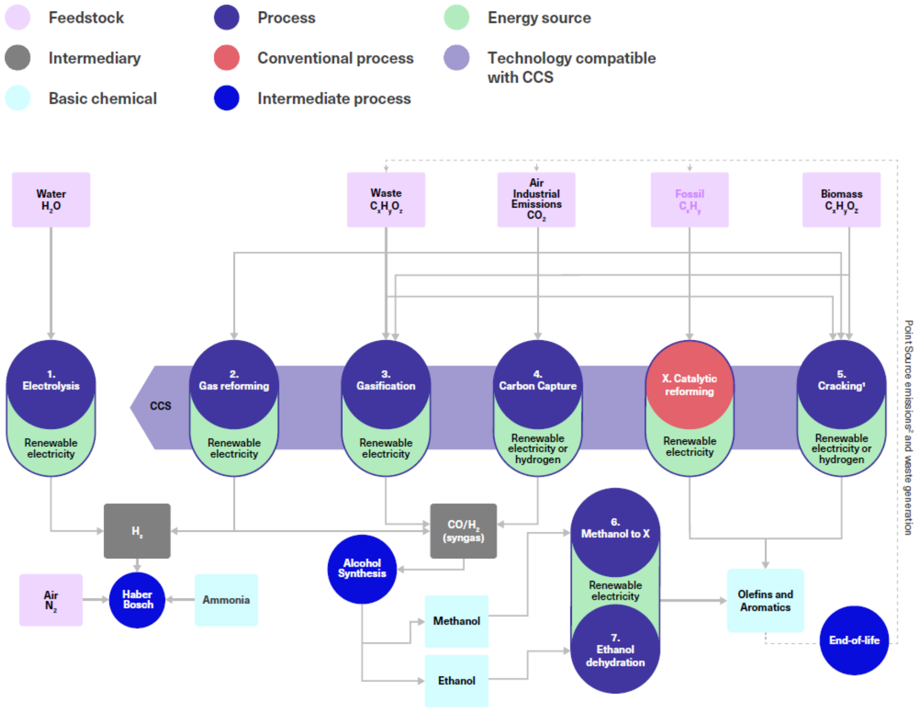

Figure 31 : Production processes and GHG mitigation options for key base chemicals .

Source: University of Tokyo, Center for Global Commons and Systemiq 2022.

The potential of the above GHG mitigation options for a zero-emission chemical industry can be divided into 45 % through energy efficiency, electrification and the use of CO_2 -free electricity, 25-30 % through the use of hydrogen, biological carbon sources and closed-loop use of CO_2, and 25 % through the use of CCS (Figure 32).[121]

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[121] Cf. Saygin & Gielen, 2021.

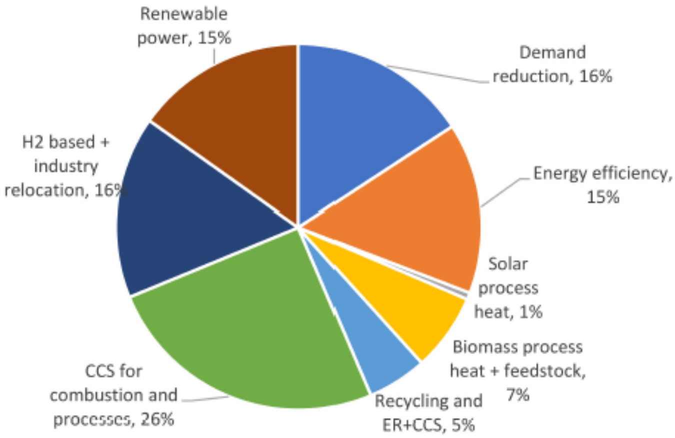

Figure 32 : Percentage share of different GHG reduction options for an emission-free chemical industry in 2050 .

Source: Saygin & Gielen, 2021.

A further analysis of a possible technology mix based on different scenarios (Figure 33) also shows that decarbonisation or better a GHG emission-free chemical industry cannot be achieved through one key technology. Rather, due to the complex processes and production chains, all possible options become necessary and have to be scaled accordingly.

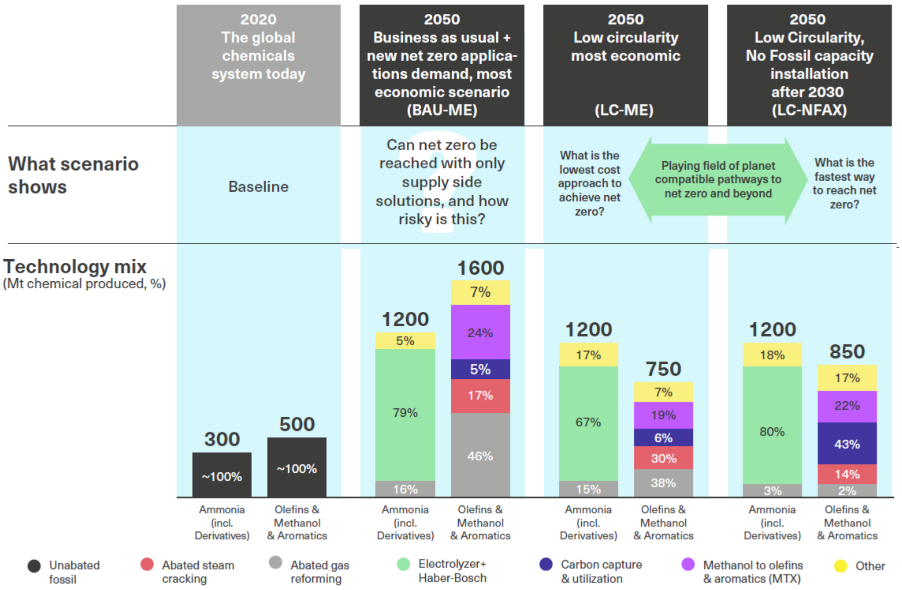

Figure 33 : Necessary technology mix for a GHG emission-free chemical industry in different scenarios in 2050.

Source: University of Tokyo, Center for Global Commons and Systemiq, 2022.

Application examples

Electrically heated steam cracker furnaces (BASF, SABIC, Linde)

Many basic chemicals as well as the processing and splitting of certain products require high temperatures. Steam cracker furnaces are often used to break down fossil hydrocarbons into other products and process them further. BASF's steam cracker furnaces reach temperatures of 850°C and have so far been fired primarily by fossil fuels via natural gas.

BASF, in cooperation with SABIC and Linde, has started construction of the world's first demonstration plant for large-scale electrically heated steam cracker furnaces in September 2022. By using electricity from renewable sources instead of natural gas, this technology has the potential to reduce the GHG emissions of this very energy-intensive production process by at least 90 %.

In the demonstration plant, which will be fully integrated into an existing steam cracker at BASF's Ludwigshafen site, a direct and indirect heating concept will be tested (Figure 34). The project is financially supported by the BMWK funding programme "Decarbonisation in Industry". Commissioning of the plant is planned for 2023 and is expected to process 4 tons of hydrocarbons per hour, using 6 MW of renewable energy. [122]

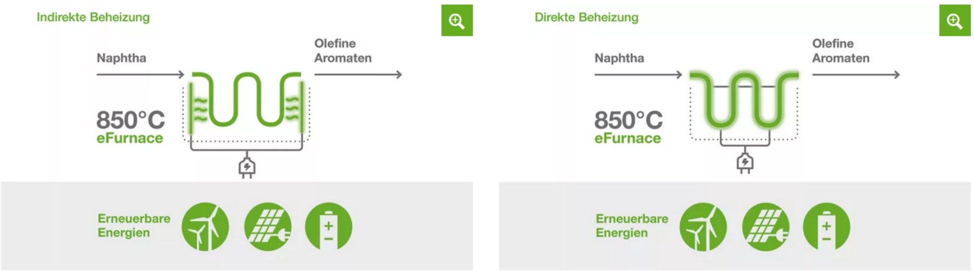

Figure 34 : Heating concepts of the demonstration plant of an electrically heated steam cracker furnace of BASF.

Source: BASF, 2022.

Project Air: climate-neutral methanol (Perstorp, Fortum, Uniper)

The project partners, Perstorp, Fortum and Uniper want to produce sustainable and climate-neutral methanol in the Air project using a circular economy for carbon.

With the help of a combination of different technologies, such as carbon capture and utilisation (CCU), CO_2, residues, renewable hydrogen and biomethane are to be converted into methanol (Figure 35). Production is expected to start in 2026 at the Perstorp site in Stenunsung, Sweden, and provide a carbon-negative solution in less than five years (130 % less CO_2 emissions due to the use of biogenic CO_2 sources).

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[122] Cf. BASF, 2022.

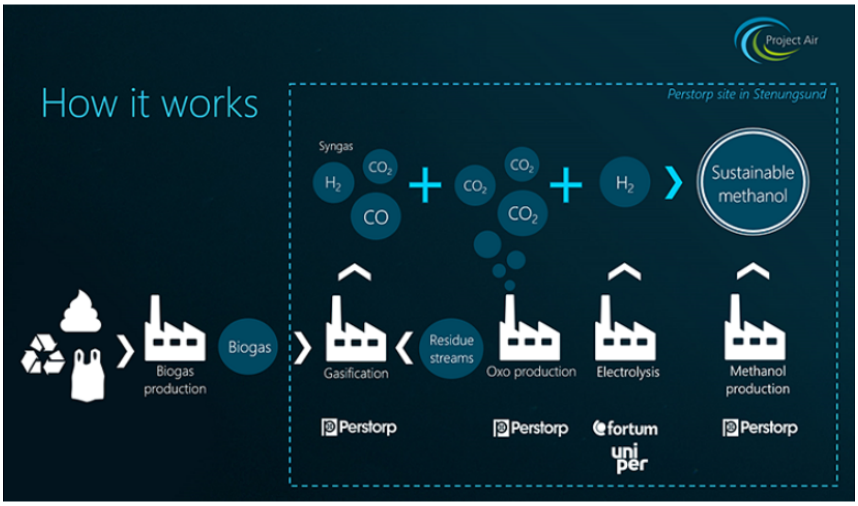

Figure 35 : Process for producing climate-neutral methanol by Project Air.

Source: Perstorp, 2022.

The process and technology can also be scaled up and will replace all the fossil produced by Perstorp in the EU, providing sustainable chemical products for European industries and sectors.

The project partners expect a CO_2 reduction of 500,000 tonnes per year from 2026, which is equivalent to the annual emissions of approximately 340,000 new fossil fuel cars or 1 $ of Sweden's CO_2 emissions. The project is supported by € 97 million from the EU Innovation Fund and € 30 million from the Swedish Energy Agency. The project partners estimate the total investment at € 230 million.[123]

3.2.3.4 Developmental relevance

The chemical industry has already internationalised in the past 10-20 years. China, India and countries in the Middle East have recorded the highest growth rates. Demand for chemicals is currently concentrated in industrialised countries. However, since the countries of the global South are steadily catching up in their economic development, the demand for many products of the chemical industry could also increase strongly there.

Important factors for the development or location of chemical industries in a country are demand and access to low-cost fossil raw materials (especially oil and gas, but also coal in some countries such as South Africa and China). To enable the transformation of the chemical industry to a climate-neutral economy, access to low-cost renewable energy, biomass and CO_2 disposal sites will also become increasingly relevant for future location decisions. These new factors could favour the development of chemical industrial complexes, especially in emerging and developing countries. This is especially true if the production of electricity from wind and solar energy is cheaper in these

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[123] Cf. Project Air, 2022.

countries than in industrialised countries. The low-cost production of renewable hydrogen can be concentrated in remote desert areas, for example, in the Middle East, Africa, Australia and Chile.

The production of products such as ammonia, methanol and other chemicals could also take place close to hydrogen production sites to reduce transport costs. The global transport of important chemicals and their bases can become a significant economic sector for the respective countries.

The following thematic areas therefore appear to be the most relevant in the context of development cooperation:

- Potential analyses for the production of climate-neutral and cost-effective chemical products
- Establishing international supply chains for sourcing climate-neutral chemical products from production areas
- Cooperations for the development of novel plant concepts and demonstration plants in emerging and developing countries

3.2.4 Other industries: Pulp and paper

3.2.4.1 Presentation of global production volumes and emissions

As one of the largest industrial sectors in the world, the pulp (cellulose) and paper industry has a high energy consumption. In general, a distinction must be made between pulp production and paper production. The latter uses pulp as an input material. The end product in paper manufacturing can be very different and includes packaging materials and cardboard, graphic paper for printing and pulp products such as paper handkerchiefs. In the following, the pulp and paper industry is considered as a whole, but the energy consumption and emissions of the pulp and paper industry are differentiated by process. Pulp production accounts for 13 - 15 % of global wood consumption and 33 - 40 % of all industrial wood traded worldwide.[124] The paper industry has increased its production by about 60 % since 1990 (Figure 36).

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[124] Cf. WWF, 2022.

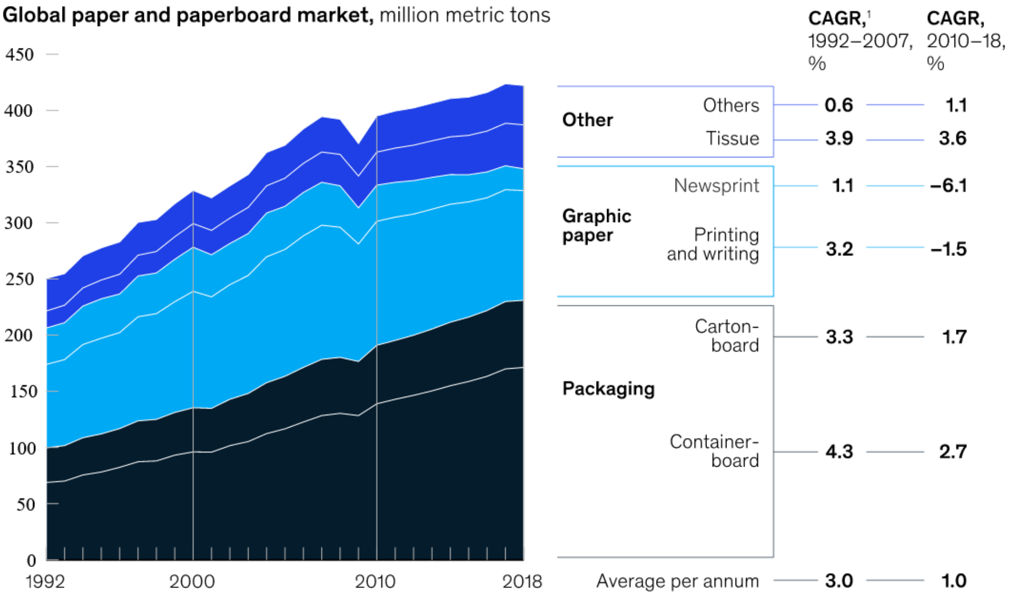

Figure 36 : Global paper and board market in million tonnes 1992-2018 (CAGR: annual growth rate).

Source: Berg & Lingqvist, 2019.

In the past five years, paper consumption grew only slowly or even declined for certain products. The estimated global production volume of paper and board in 2020 was around 398 million tons (Mt), with consumption at 402 Mt.[125]

Compared to the previous year, this represents a decrease of 10-15 Mt. The two largest paper producing and also consuming countries in the world are China and the United States (Figure 37). Europe is at the consumption and production level of China.

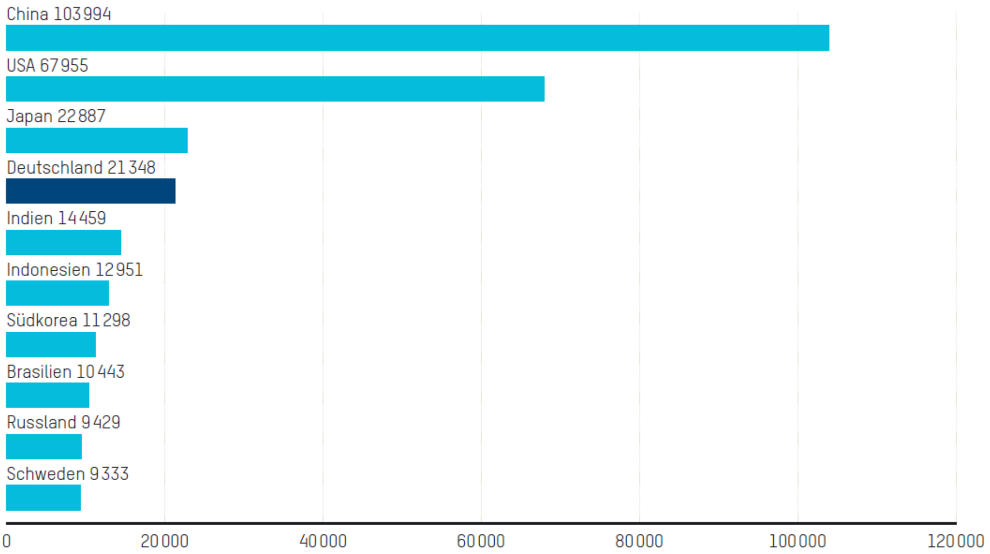

Figure 37 : Top ten paper, board and cardboard producing countries in 2020.

Source: Die Papierindustrie e.V., 2022.

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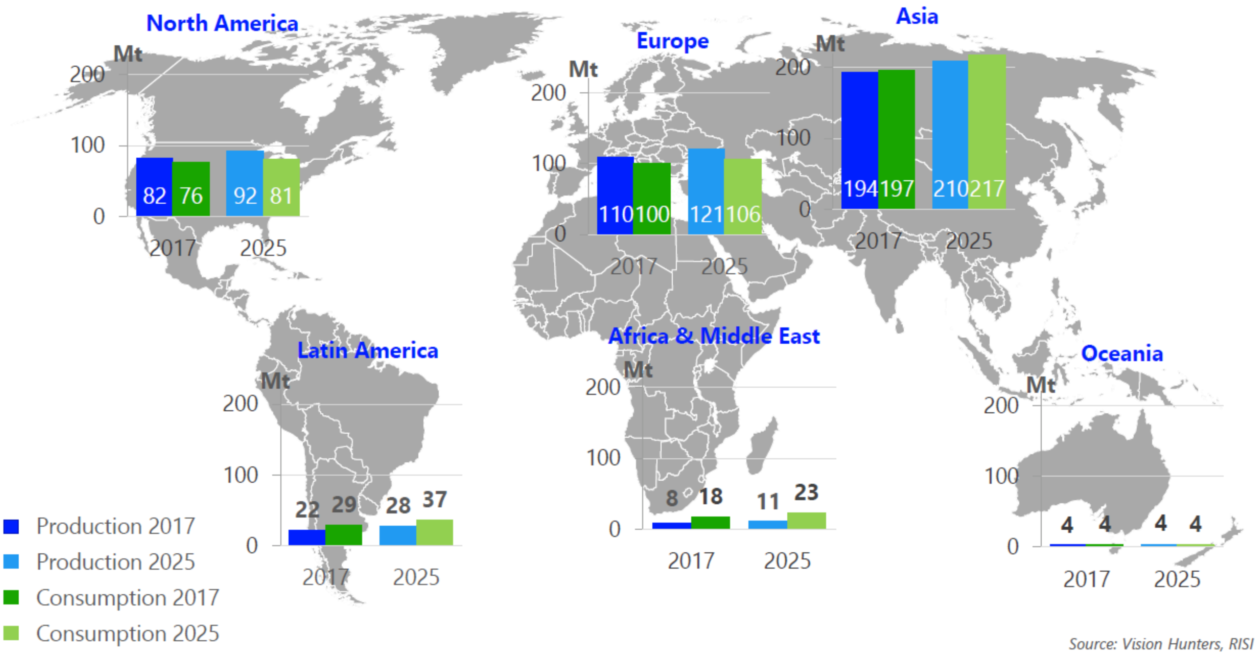
[125] Cf. Die Papierindustrie e.V., 2022.

While consumption in industrialised countries is estimated to be stable, estimates for developing and emerging countries assume that consumption will increase. There are different estimates for the future, which are summarized in Table 4.

	2032	**2050**	**2065**
Paper consumption in Mt	476	550, 770, 900	615
Year of estimate	2022[126]	2019,[127] 2011,[128] 2009[129]	2019[130]

Table 4 : Estimate of future paper consumption worldwide.

Developments in web-based information provision and delivery services for end products make growth to around 500-600 Mt in 2050 seem realistic. Stronger growth is expected especially in Africa, Latin America and Southeast Asia (Figure 38 and Figure 39).



Source: Vision Hunters, RISI

Figure 38 : Development of paper production and consumption by world region until 2025.

Source: Häggblom, 2018.

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[126] Cf. Statista, 2022 .
[127] Cf. Furszyfer Del Rio et al., 2022.
[128] Cf. Cepi, 2011.
[129] Cf. IEA, 2009.
[130] Cf. Johnston & Radeloff, 2019.

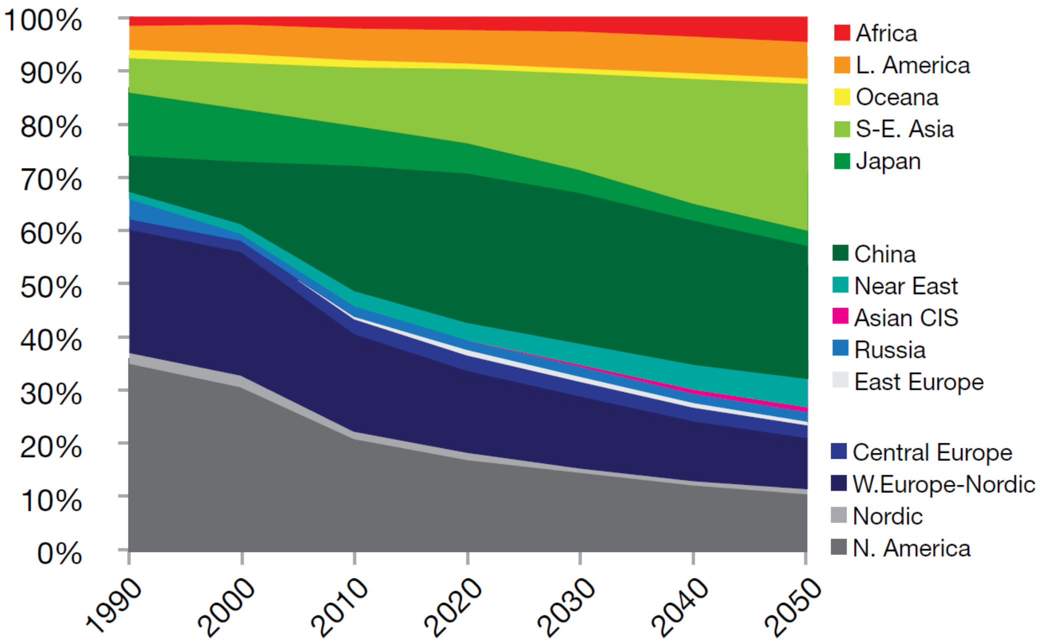

Figure 39 : Global demand for paper and board by region.

Source: Cepi, 2011.

The pulp and paper industry is one of the five most energy-intensive industries worldwide and the fourth largest industrial energy consumer. The production of pulp and paper is complex because, especially in the production of pulp, there are different processes with different energy consumption. Globally, about 6 % of industrial energy consumption and about 0.3 - 0.45 Gt or 1 - 2 $ of global GHG emissions come from the paper sector.[131]

The CO_2-intensity of the paper industry varies greatly depending on the country, the fuels used, the electricity mix and the production process. However, the CO_2 intensity of paper production has already been greatly reduced in recent decades due to higher efficiency in the production process and the increased use of biogenic fuels. In industrialised countries, the CO_2 intensity decreased by 50 % or more compared to 1990. However, as the quantities produced increased by a similar factor and production increased worldwide in countries with lower energy efficiency and thus higher specific emissions, GHG emissions remained at a stable level globally in recent years. An overview of the specific emission levels at different times in different countries and regions is given in Figure 40.

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[131] Cf. Furszyfer Del Rio et al, 2022; van Ewijk et al, 2021.

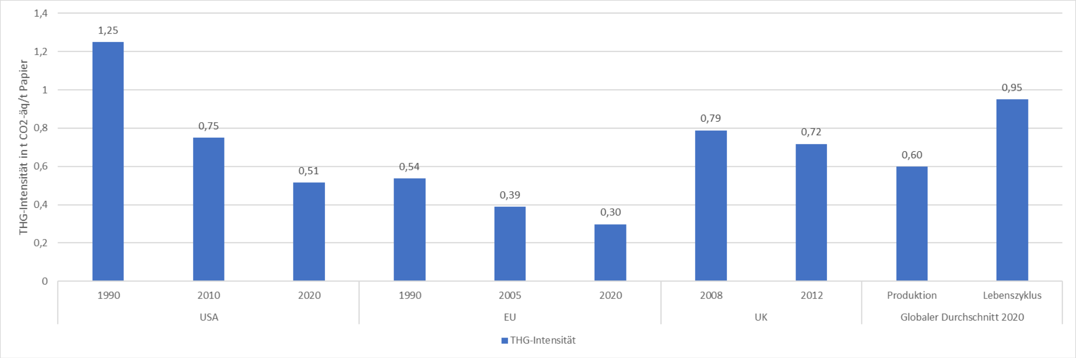

Figure 40 : Greenhouse gas intensity of the pulp and paper industry in different regions and years.

Data sources: American Forest & Paper Association, 2014; EPA, 2022; Die Papierindustrie e.V., 2022; Cepi, 2020; WSP, Parsons Brinckerhoff and DNV GL, 2015; Sun et al, 2018; Furszyfer Del Rio et al, 2022.

A major problem in comparing the figures is the system boundary and the type of mill and end product. For example, the global average CO_2 intensity for pulp and paper production is assumed to be 0.6 - 0.95 t CO_2 /t paper.[132] Another study, which considers the entire life cycle including upstream and downstream emissions of the pulp and paper industry in China, arrives at a much higher emission intensity of 1.95 - 6.52 t CO_2 /t paper.[133] The most important energy and emission-related parameters of pulp and paper production are shown in Table 5 summarised in Table 5

Parameter	Values
Energy intensity of paper production (total process)	5-35 GJ/tonne paper (depending on process), average: 11-15 GJ/tonne paper
Energy intensity of paper production (individual processes)[134]	**Pulp production** 2000-2500 kWh/t electricity (mechanical processes) 700 kWh/t electricity, 3000-4000 kWh/t heat (chemical processes) 150-600 kWh/t electricity, 0-350 kWh/t heat (recycled fibres) **Paper production** 200-1000 kWh/t electricity, 900-1700 kWh/t heat
Emission intensity of paper production	0.6-0.95 t CO_2 /tonne of paper (efficient production process) 1.95-6.52 t CO_2 /tonne of paper (coal-based production process) 3-10 t CO_2 /tonne paper (entire life cycle including biogenic GHG emissions)
emissions in the manufacturing process (2020)	300-450 Mt CO_2 -eq (including biogenic GHG emissions)[135] 190 Mt CO_2 -eq (excluding biogenic GHG emissions)[136]
Pulp and paper production (2020)	400 Mt

Table 5 : Energy and emission-related parameters of pulp and paper production.

When examining the emissions that occur during the production of pulp and paper, however, a distinction must be made between the entire life cycle and the pure manufacturing process of pulp or paper itself. In the first case, direct and indirect emissions due to the use of biomass from plantations

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[132] Cf. Furszyfer Del Rio et al., 2022.
[133] Cf. Sun et al., 2018.
[134] Cf. Navigant, IER, Ffe, BBG and Partners, 2019.
[135] Cf. Furszyfer Del Rio et al., 2022.
[136] Cf. IEA, 2022b.

or sustainable forestry (FSC or PEFC) as well as due to the transport of the wood or paper are also included. This chapter focuses primarily on the sources of emissions in the manufacturing process, as relevant indirect emission sources are explained in other chapters (Chapter 3.3 Transport and Chapter 2.10 Nature-Based Solutions).

Nevertheless, the overview of all emission sources assigned to the life cycle of paper production in Figure 41 should allow a classification. About 50 % of the emissions over the life cycle are associated with the use of the raw materials wood or biomass. It is important to note here that the combustion of biomass can be climate-neutral in itself, since the greenhouse gases emitted were previously bound in the biomass by being removed from the atmosphere.

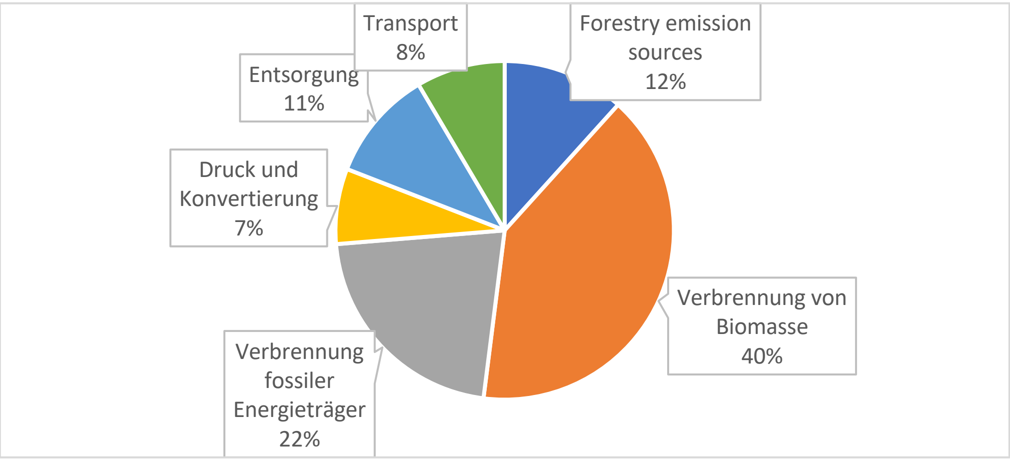

Figure 41 : Proportionate greenhouse gas emissions over the life cycle of paper production.

Source: European Environmental Paper Network, 2013.

3.2.4.2 Energy consumption and sources of CO emissions$_2$

The manufacturing process

Since the emissions in the manufacturing process are mainly considered in the further course, it is important to understand this complex process. The system boundary is drawn here at the factory gate of the pulp or paper production plant. The manufacturing process can take place in different ways (Figure 42 and Figure 43). The majority of pulp production (EU: 70 %, global: 90 %) takes place in specialised pulp mills. The pulp is then processed into paper products in paper mills. However, there are also integrated paper mills where both pulp and paper production take place on the same site.

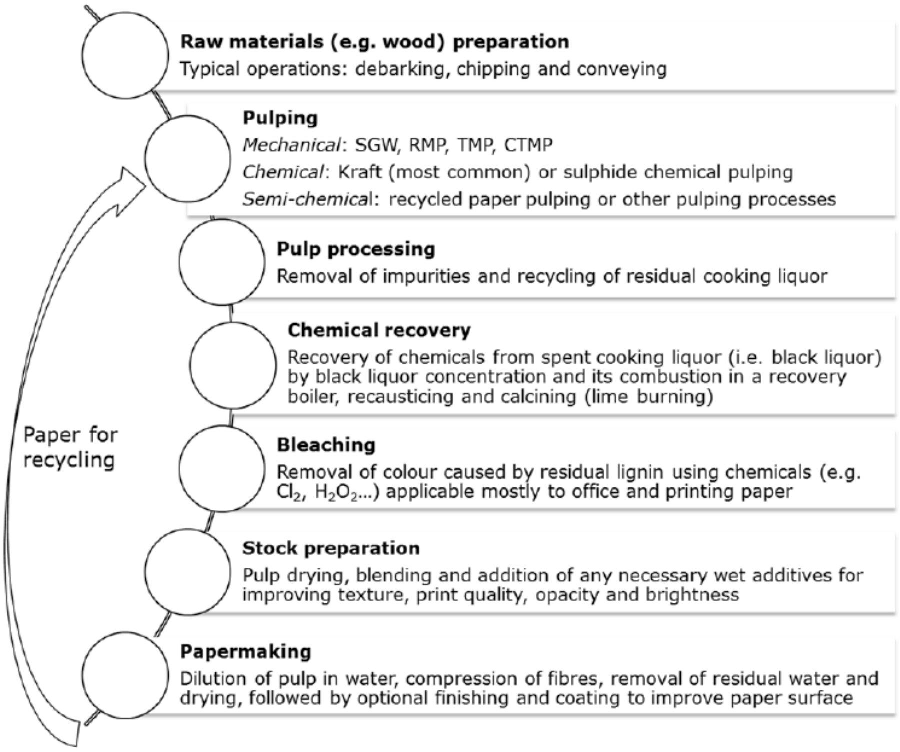

Figure 42 : Pulp and paper production processes.

Source: Moya & Pavel, 2018.

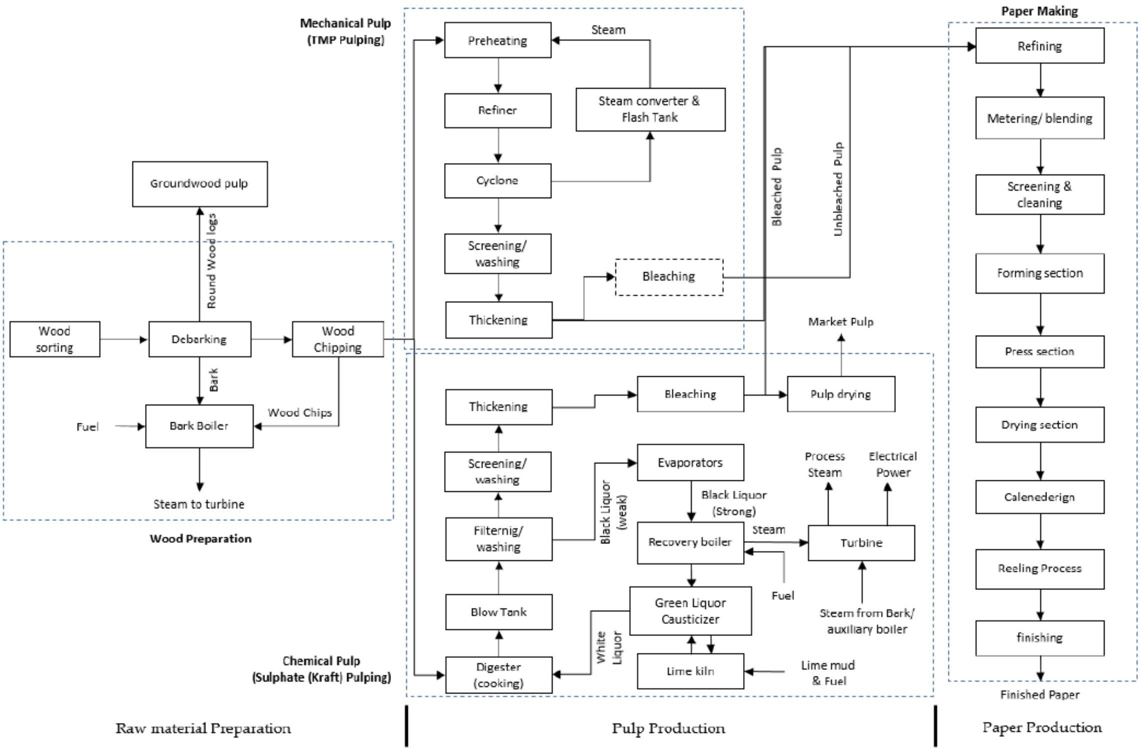

Figure 43 : Process diagram of various paper manufacturing processes.

Source: Mobarakeh et al., 2021.

The following process description of paper production is based on a number of publications and is only intended to provide an overview, but not a detailed description of the individual process steps.[137] Pulp and paper are produced from cellulose fibres and other plant materials. In general, softwoods (e.g. pines, firs and spruces) provide long and strong fibres that give paper strength and are used for boxes and packaging. Hardwoods produce a weaker paper as they contain shorter fibres. Softwoods are smoother, transparent and more suitable for printing.

Preparation of the raw material

The wood delivered to a pulp mill can be in different forms. This depends on the pulping process (breaking the fibre bonds) and the origin of the raw material. It can be in the form of logs with bark still attached or as chips produced in a sawmill from debarked logs. If roundwood is used, it is first debarked. This usually takes place in large steel drums. The debarked logs are then chipped in a chipper if the pulping process requires chemical pulping. The chips are then sorted by size, cleaned and temporarily stored for further processing and fed to the other processes as required. Waste paper can also be recycled and, after cleaning and partial blending with new fibres, can be reintroduced into the pulp production process. Over 50 % of the pulp produced worldwide is made from recycled paper. [138]

Wood pulping and pulp production (pulping)

In the fibre separation phase different pulping processes are used: mechanical, chemical or a combination of the two. In 2016, about 77 % of the total pulp produced in the EU was produced by chemical processes and 23 % by mechanical processes.[139] Globally, the chemical kraft process accounts for more than 90 % of pulp production.[140] The production of pulp by the chemical pulping process takes place in special pulp mills, which are only very rarely directly integrated with paper production.

The mechanical process is the oldest form of wood pulping, in which the fibres are weakened and separated from the wood through comminution (wood grinding) and the application of heat. Various mechanical processes can be used for pulping (stone groundwood-SGW, thermo groundwood-TGW, pressurised groundwood-PGW, refiner mechanical pulping-RMP, thermomechanical pulping-TMP and chemi-thermomechanical pupling-CTMP). These differ in terms of the machinery used and the temperature level required. Electricity is the main source of energy in mechanical pulping. Most

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[137] Cf. Moya & Pavel, 2018; Ochre Media, 2022; Mobarakeh et al, 2021.
[138] Cf. Furszyfer Del Rio et al., 2022.
[139] Cf. Cepi, 2022.
[140] Cf. Furszyfer Del Rio et al., 2022.

of it is converted into electricity in the process and parts of it can be recovered and used in other processes or for district heating.

In the chemical process, the fibres are extracted from the wood in a cooker under pressure using "cooking chemicals" and separated by washing. Depending on the type of chemicals used for digestion, two main processes are distinguished: Kraft (or sulphate) and sulphite. In the Kraft process, a strongly alkaline solution (white liquor) containing sodium hydroxide (NaOH) and sodium sulphide (Na_2S) is used for digestion. In the sulphite process, on the other hand, wood decomposition takes place in an acidic mixture (sulphite cooking liquor) of sulphurous acid (H_2SO_3) and bisulphite ions (HSO_3). The black liquor produced during wood cooking and further treated in the recycling circuit is an energy-intensive by-product of the pulp manufacturing process. It contains wood waste, chemicals and other impurities. This liquor is burnt on site in the power plant's recovery boiler. This produces steam that can later be used in a steam turbine to generate electricity.

Bleaching process

Depending on the end use, pulp can be bleached with various chemicals (e.g. chlorine dioxide, hydrogen peroxide, oxygen, caustic and sodium hypochlorite) to produce bright or white papers, which are preferred for many products. Before it is made into paper, the pulp goes through several steps called stock preparation. Stock preparation may also involve mixing and adding additives (e.g. resins, waxes for water repellency, and certain inorganic chemicals) to improve texture, print quality, opacity and brightness.

Paper production

The pulp can now be further processed into paper. In the first and often very energy-intensive process, the moisture is reduced by various mechanical and thermal processes. In the process, the pulp is pressed into rollers, thereby converting it into a thinner material. To improve the surface quality, the paper can be subjected to additional processes after drying. This finishing and coating is done with dyes, pigments and binders. During the finishing process, the paper rolls are cut into smaller rolls with a slitter rewinder.

Integrated mills (pulp and paper) can be more energy efficient than non-integrated mills (paper only), as energy generation and waste heat utilisation can be better optimised in integrated mills.

Energy consumption in the manufacturing process

Due to the wide range of pulp production processes, the energy input varies depending on the raw materials used, the paper quality and the techniques applied. The specific energy consumption for one and the same process can also vary greatly due to the different composition of the raw material, the different process methods and the use of different technologies. Mechanical and thermo-mechanical pulping (TMP) mainly requires electricity to drive the grinding and shredding equipment, while chemical pulping relies heavily on steam. However, heat and electricity can be generated by burning the biomass residues that are a by-product of chemical pulping. This allows some pulp mills to generate more electricity than they need. In the papermaking process itself, drying is the most energy-intensive step and accounts for about two-thirds of the total energy consumption in papermaking. The average energy consumption of different process steps is shown in Figure 44 and Table 6 are shown.

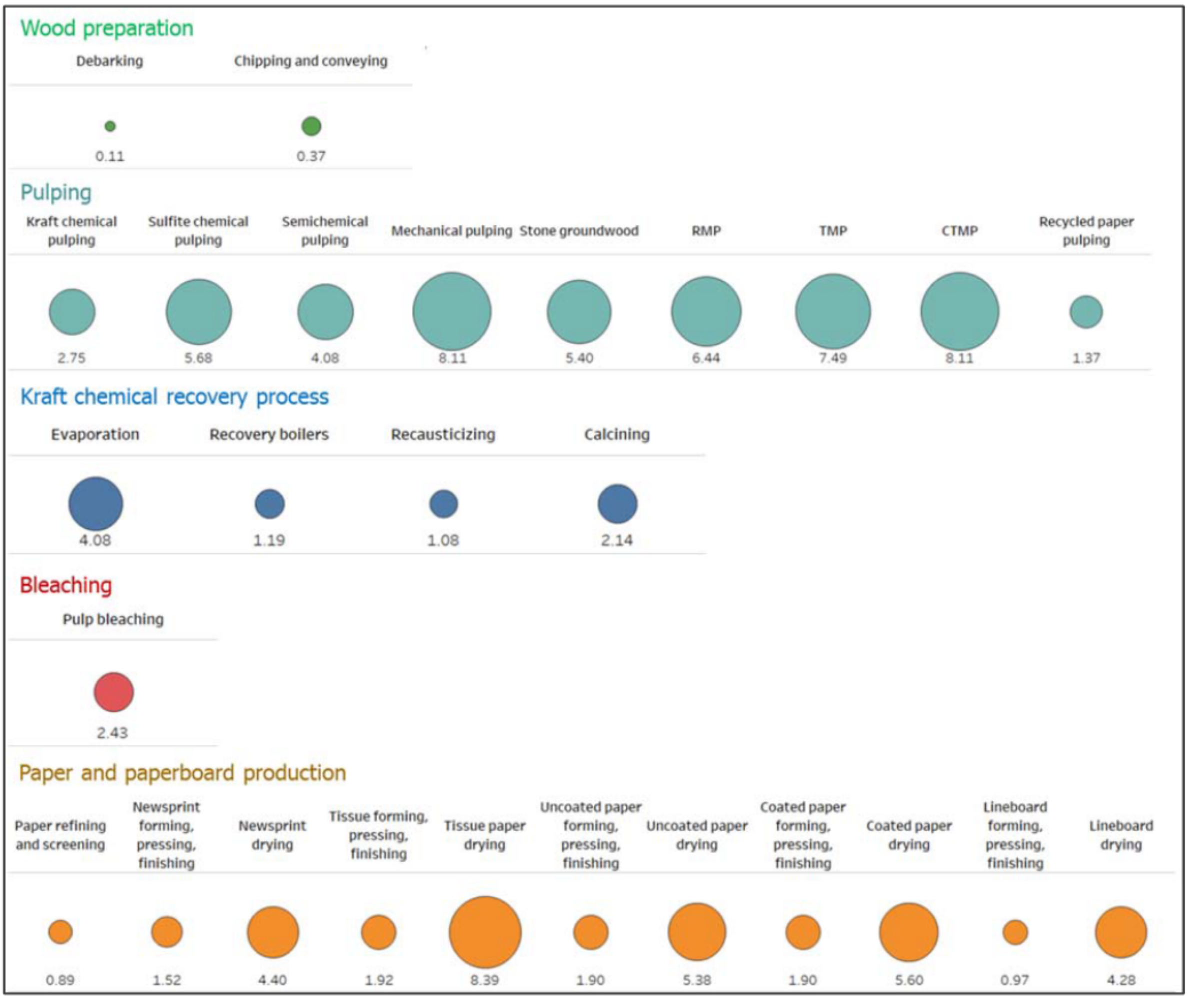

Figure 44 : Average energy consumption in GJ/tonne for pulp and paper manufacturing processes. Source: Moya & Pavel, 2018.

Process	**Work step**	**Power consumption**	**Heat consumption**
		kWh/t wood	GJ/t wood
Raw material processing	Debarking	7-10	0
	Crushing and onward transport	30	0
		kWh/t air-dry pulp	**GJ/t air-dry pulp**
Mechanical wood pulping	Wood pulp	1100-2200	0
	RMP	1600-3000	0
	TMP	1800-3600	0,9
	Washing and sieving	50	
	Bleaching	100	

Chemical wood pulping	Force procedure	406	2,4-5,6
	Sulphite process	226-1360	4,1-6,5
	Washing and sieving	30	0
	Delignification	75	0,5
	Bleaching	60-185	4,3
	Chemical reprocessing	133	4,1-9,2
	Drying	90-160	2,5-4,5
Pulp production from recycled paper	Fibre digestion	265-429	0
	Seven	50	0
	Decolourisation	80	0
	Concentration	40	0,5
	Bleaching	30	
		kWh/t paper	**GJ/t paper**
Paper production	Moulds and presses	270-533	0
	Drying	15-132	4.2-5.5

Table 6 : Specific electricity and heat consumption of various manufacturing processes and steps for pulp and paper.

Source: Mobarakeh et al., 2021.

The production of one ton of paper requires on average about 11 - 15 GJ (depending on the process 5 - 35 GJ) of primary energy and is comparable to the production of other energy-intensive products such as steel or cement.[141] Due to the multitude of processes, the subdivision into pulp and paper production (integrated or non-integrated) and the use of different energy sources (wood, gas, coal, heat, electricity), a comparison of manufacturing processes and individual mills is extremely complex. According to a study of more than 60 paper manufacturing plants, pulp production accounts on average for 62 $ of energy consumption and 45 % of GHG emissions.[142] Another study found that pulp production accounts for about 94 % of heat consumption and 47 % of electricity consumption, but paper production accounts for only 5 % of heat consumption but 42 % of electricity consumption.[143] In the EU, 93 % of total energy consumption is for heat energy and the remaining 7 % for electricity. In a study of the paper industry in Austria, nearly 74 % of the final energy is divided between steam generation in the drying and separation processes, 20 % between electric motors, 3 % between industrial furnaces and just under 3 % between the energy consumption of the building.[144]

CO_2 emissions in the pulp and paper industry

Major sources of emissions in the pulp and paper industry over the entire life cycle are shown in Figure 45 Figure 45.

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[141] Cf. Moya & Pavel, 2018; Furszyfer Del Rio et al, 2022.
[142] Cf. Sun et al., 2018.
[143] Cf. Furszyfer Del Rio et al., 2022.
[144] Cf. Mobarakeh et al., 2021.

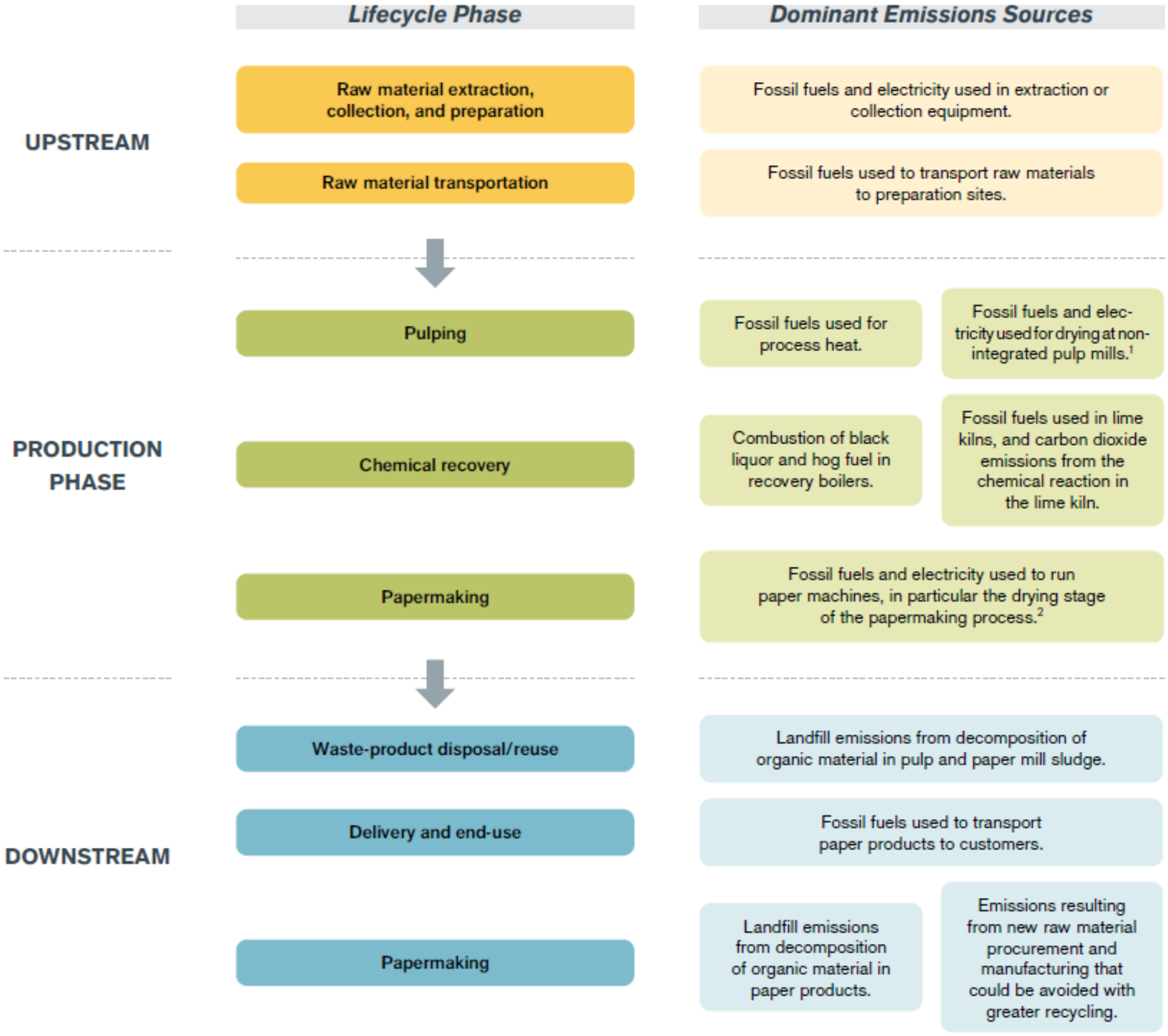

Figure 45 : GHG emission sources of pulp and paper over the life cycle.

Source: Clean Energy Transition Institute, 2022.

Indirect emissions from the purchase of raw materials and their transport, as well as emissions from landfilling or the incineration of waste paper, are only marginally considered in the following analysis of CO_2 reduction options. However, in terms of a holistic approach to emissions reduction, the pulp and paper industry must also consider downstream emissions in particular. Through increased material efficiency and the development of an even more extensive circular economy, the sector can avoid further emissions here as well.

Despite its high energy consumption, the pulp and paper industry is one of the least CO_2 -intensive industrial sectors in Europe and worldwide. This is due to the high use of biomass as a primary energy source.[145] Similarly, specific GHG emissions per ton of paper produced have been greatly reduced in recent years, at least in industrialised countries (Figure 40). The use of biomass as a fuel, increased process efficiency, the use of waste heat and the decreasing emission factor of the

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[145] Cf. Moya & Pavel, 2018.

electricity purchased from the grid due to the expansion of renewable energies played the most important role here.[146] Nevertheless, the pulp and paper industry has one of the highest carbon intensities of all industries (measured as t CO_2 e per USD of gross value added). Energy accounts for about 16 % of industry costs on average, but up to 30 % depending on the country.[147]

A large part of the emissions are generated in the wood pulping processes. The GHG emissions from the production of pulp by different processes are: [148]

- Kraft process: 508 kg CO_2-eq/t;
- Chemical-mechanical process: 513 kg CO_2-eq/t;
- Recycled pulp: 408 kg CO_2-eq/t.

Since the Kraft process accounts for 70 - 90 % of production, depending on the region, this process generates about 70-80 % of the emissions from the pulp and paper industry worldwide.[149] The sources of CO_2 emissions are the kilns for lime and the power plants for generating heat and electricity (Figure 45 and Figure 46). It should be pointed out once again that the use of biogenic fuels reduces fossil emissions. The process of pulp production and, in the case of integrated plants, also paper production can therefore take place with a lower CO_2 intensity or, in some cases, even in a climate-neutral manner.

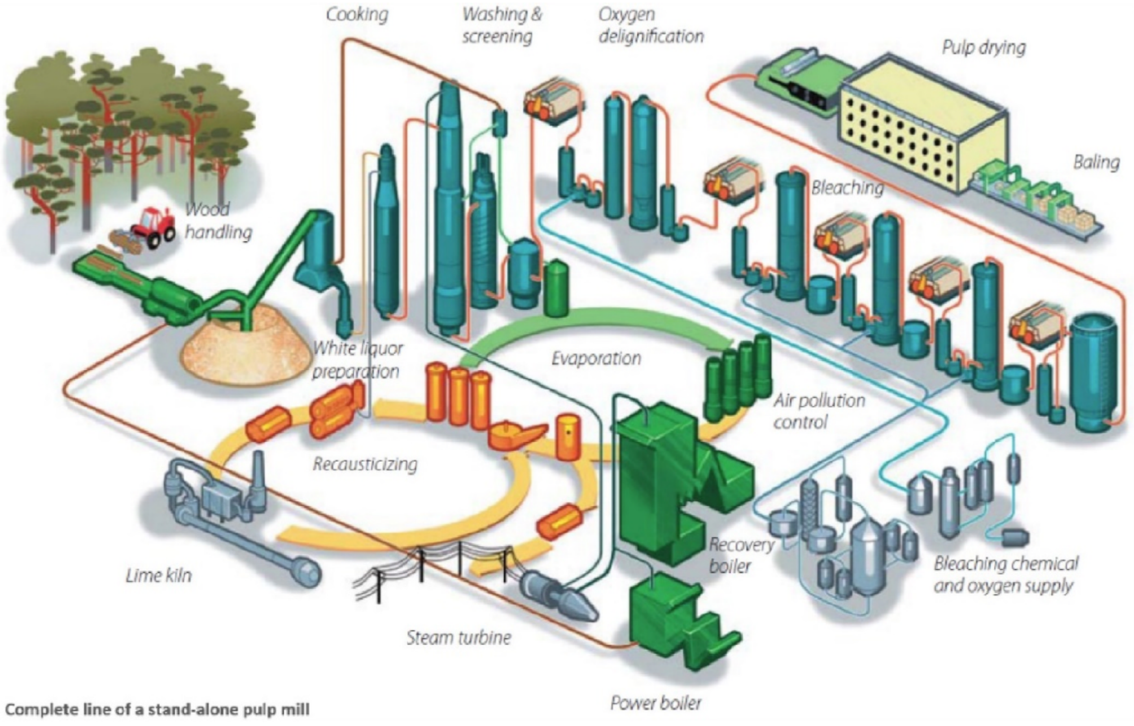

Figure 46 : Closed-loop chemical pulp production plant. Source: Furszyfer Del Rio et al., 2022.

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[146] Cf. WSP, Parsons Brinckerhoff and DNV GL, 2015.
[147] Cf. Furszyfer Del Rio et al., 2022.
[148] Cf. Sun et al., 2018.
[149] Cf. Furszyfer Del Rio et al., 2022.

3.2.4.3 Technical options for CO_2 reduction

An in-depth investigation of all measures to decarbonise the entire supply chain and downstream emissions is beyond the scope of this chapter. However, detailed studies exist on this topic. [150]

In addition to the regeneration of forests, the use of non-wood biomass in the manufacturing process is also a way to avoid GHG emissions in the upstream supply chain. In the production process of pulp and paper, there are a number of mitigation potentials through increased resource, energy and waste efficiency. Replacing old technologies with more efficient equipment, making greater use of by-products (waste biomass for energy generation) but also the capture, utilisation and storage of CO_2 emissions (CCUS) offers great potential. Process optimisation and the replacement of fossil fuels are at the forefront of chemical reprocessing. Increased recycling rates and reuse of pulp and paper products can also lead to lower life-cycle GHG emissions. Figure 47 and Figure 48 represent sub-sectors of the industry and possible approaches and options for GHG emission reduction.

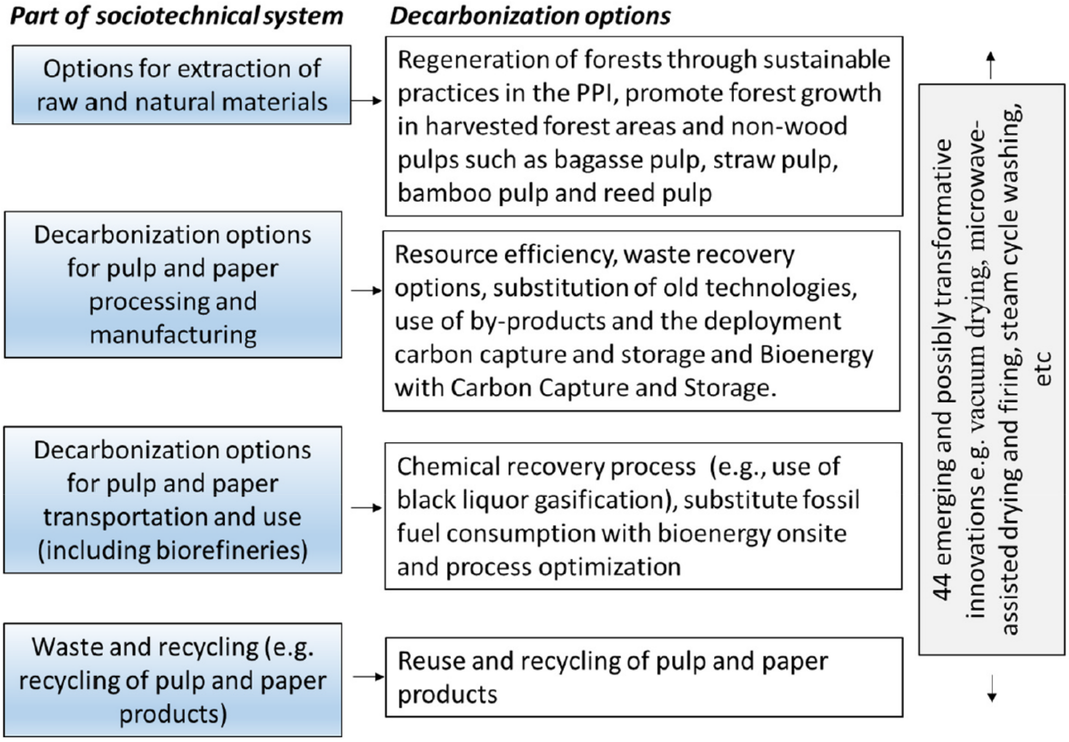

Figure 47 : GHG mitigation and decarbonisation options over the pulp and paper life cycle.

Source: Furszyfer Del Rio et al., 2022.

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[150] Cf. Moya & Pavel, 2018; Mobarakeh et al, 2021; WSP, Parsons Brinckerhoff and DNV GL, 2015; Furszyfer Del Rio et al, 2022.

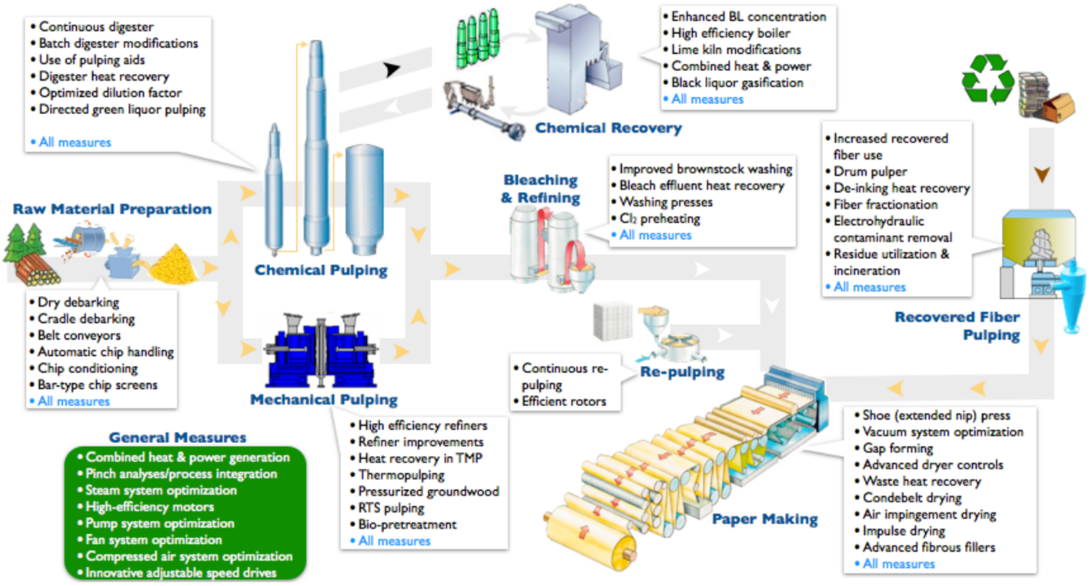

Figure 48 : Technical and operational measures to increase process and energy efficiency and GHG savings in pulp and paper production.

Source: Institute for Industrial Productivity, 2013.

In the following, some of the options are examined in more detail, with a focus on production processes in industry.

Use of biomass

The use of biomass as a fuel for electricity and heat generation is a major lever for reducing fossil GHG emissions in the sector. Both biogenic by-products and waste products as well as original biomass can be used in the factories' own power plants and combustion processes. In Europe and the USA, biomass accounts for about 60 % of energy production.[151] In many Asian countries, however, the share of fossil fuels, especially coal, is still relatively high. An overview of the energy sources used in different regions of the world is shown in Figure 49 is shown.

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[151] Cf. American Forest & Paper Association, 2021; Cepi, 2022.

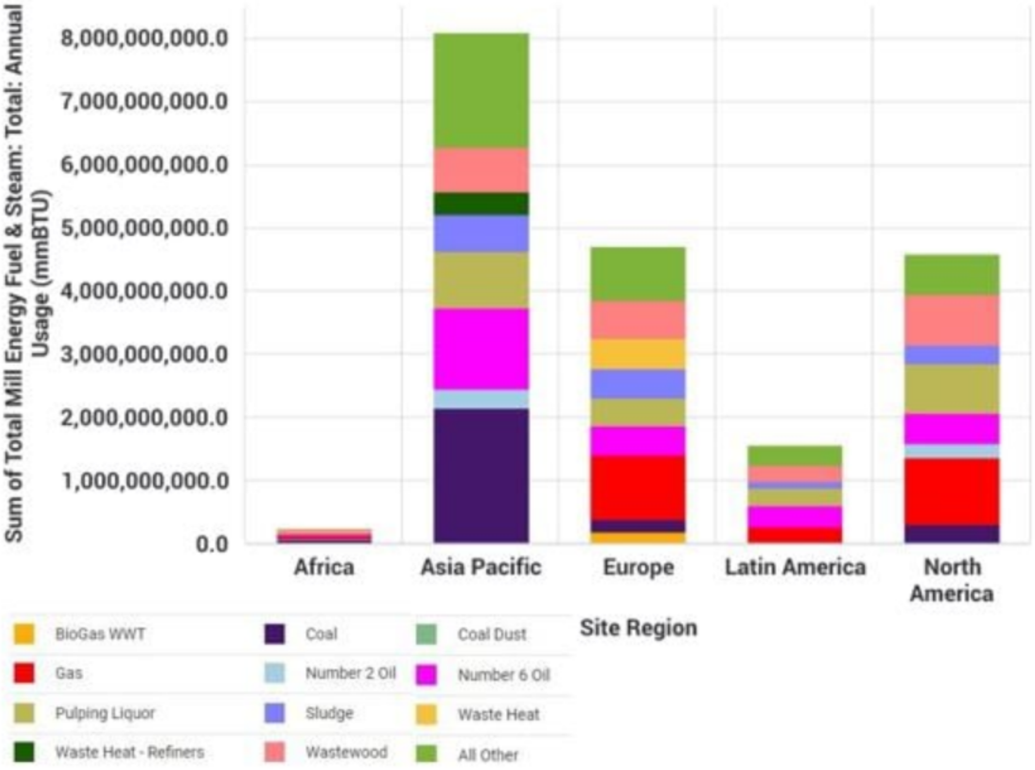

Figure 49 : Energy sources used in the pulp and paper industry in different world regions.

Source: Fisher International, 2022.

The integration of biomass as an energy source in the paper production process can still be optimised in many countries. The use of biogenic by-products and waste can also play an important role here.

Combined heat and power generation

The use of combined heat and power (CHP) allows industry to reduce energy consumption and emissions. The efficiency of CHP plants running on fossil fuels or bioenergy can reach values between 85 and 92 %. The pulp and paper industry is one of the biggest users of CHP, as energy savings of around 30 % can be achieved. About 10 % of the total CHP capacity in Europe is in the pulp and paper industry, making it the third largest CHP user in the industry after refineries and the chemical industry.[152] In 2020, the European paper industry generated more than 55 % of its own electricity needs, and almost 96 % of this in CHP plants.[153] CHP is also a crucial technology for the efficient use of biomass as a fuel. Gas is also a fuel that can be used efficiently in CHP plants. The availability and cost of natural gas and the size of the site are other crucial factors for the adoption

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[152] Cf. Moya & Pavel, 2018; Furszyfer Del Rio et al, 2022.
[153] Cf. Cepi, 2022.

of CHP technology. The payback period for a new CHP system in a large plant can be around 3 years.[154]

A variety of CHP configurations can be used depending on the specific conditions of the mill to achieve the best energy efficiency and flexibility at the lowest life cycle cost. Conventional steam turbines and/or gas turbines are the most installed systems CHP systems in the pulp and paper industry. Steam turbines are associated with boiler-based systems that generate high-pressure steam by burning fuels on site (e.g. black liquor, bark, waste, liquid, solid or gaseous fuels). Gas turbines, unless the hot flue gases are used in a dryer, are combined with steam generators with heat recovery.[155]

Improved waste heat utilisation

Drying processes are among the main sources of waste heat in paper production. Therefore, technologies for providing process heat can be a useful approach to reducing emissions. Paper mills can save up to 15 % of primary energy if they use heat recovery processes through heat pumps or heat exchangers. Waste heat also occurs in the process of wood pulping and pulp production, especially in the thermo-mechanical processes, and can flow to other processes. The economic amortisation of plants for waste heat utilisation is highly case-dependent. However, periods of between 3 and 6 years can be assumed.[156]

Electrification and heat pumps

The use of low-carbon electricity is also an essential measure for decarbonisation and the reduction of GHG emissions. Using industrial heat pumps and electric boilers, electricity can be an alternative to other (fossil) fuels for the production of hot water and steam. Full electrification of drying processes could reduce emissions by over 70 %.[157] Commercial trials of heat pumps running at 160 degrees are underway, and there are already designs for heat pumps that reach 200 degrees - more than enough for some papermaking processes. The industry is also working with industrial heat pump suppliers as part of its Energy Solutions Forum.[158]

However, the possibility and usefulness of electrifying processes is highly dependent on the individual energy supply concept and the processes in a specific factory. The purchase of CO_2 -free electricity from the public grid plays a major role in the decarbonisation of electricity not produced in the factory itself.

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[154] Cf. Moya & Pavel, 2018.
[155] Cf. Moya & Pavel, 2018.
[156] Cf. Moya & Pavel, 2018; Furszyfer Del Rio et al, 2022; Mobarakeh et al, 2021.
[157] Cf. Furszyfer Del Rio et al., 2022.
[158] Cf. Packaging Europe, 2021; Cepi, 2021.

Biorefineries and recycling of biogenic residues

For the reduction of GHG emissions, especially in pulp production, the development of biorefineries is an opportunity to leverage significant technological, economic and social benefits.[159] In a variety of applications, biomass is used as a feedstock in a biorefinery to produce feedstock for the production process as well as gaseous or liquid energy carriers (Figure 50). A stronger connection and the development of synergies between the chemical and pulp industries as well as potentials for decarbonisation in both can be established through biorefineries. Possible feedstocks are wood extract, black liquor, forest biomass or other cellulosic products as well as sewage sludge.[160] Three applications (use of organic sludge, black liquor gasification and deep eutectic solvents) are described in more detail below.

Large quantities of organic sludge are produced in pulp production, which could be used elsewhere in new value chains. The recovery of energy from sludge can be made possible either directly through incineration or indirectly through physico-chemical and microbiological processes. Biofuel (through pyrolysis and bioethanol production) and/or biogas (through anaerobic digestion) can be produced. The use of these synthesis products in factories can reduce the use of new fossil and also biogenic fuels and raw materials, thereby contributing to GHG mitigation. Black liquor gasification allows synthesis gas to be produced from the organic fraction of black liquor by gasification. After treatment and conditioning, the inorganic part can be reintroduced into the chemical process of pulp production. The synthesis gas can be used to generate steam, heat and electricity in the mill. Another possibility is the valorisation through the production of biofuels such as dimethyl ether (DME) or methanol.[161] The development of deep eutectic solvents (DES) is still at the research stage. This new class of bio-based solvents is renewable, biodegradable and low-volatile. DES-based pulp technology offers a much more sustainable value chain that is energy, cost and resource efficient. Because DES pulping operates at low temperature and pressure, less energy is required, making the lignin by-product available for other applications. DES pulping is also a biorefinery concept that produces cellulose fibres for papermaking while providing high-quality hemicellulose and lignin fractions for high-volume applications. The use of DES technology could reduce energy consumption by 40 % and CO_2 emissions by 80 % throughout the value chain.[162]

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[159] Cf. Cepi, 2021b.

[160] Cf. Moya & Pavel, 2018.

[161] Cf. Moya & Pavel, 2018; Furszyfer Del Rio et al, 2022.

[162] Cf. ISPT, 2022; Cepi, 2017.

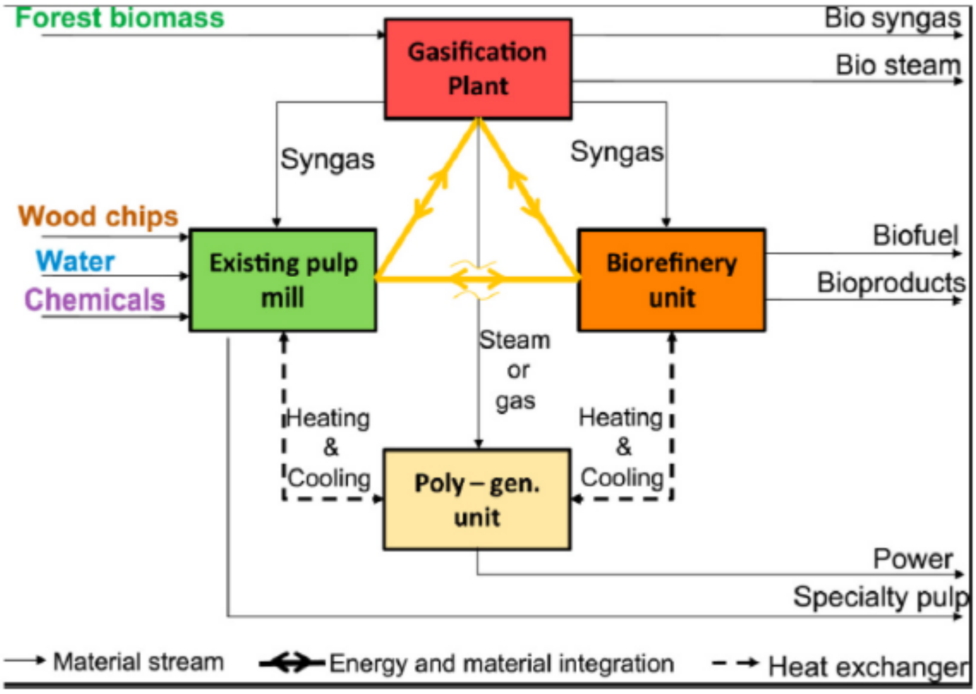

Figure 50 : Energy and material flows in a biorefinery.

Source: Furszyfer Del Rio et al., 2022.

CCUS (see also Chap. 2.8)

The use of CCUS can also play a role in avoiding CO_2 emissions in an energy-intensive industry such as paper production. In the pulp and paper industry, a large proportion of CO_2 emissions come from biomass combustion. The potential for carbon capture and storage (CCS) in pulp production is significant (CO_2 capture technologies are described in detail in chapter 2.3). The best approach is to capture CO_2 in pulp production from the flue gases of the recovery boiler or lime kiln. Capturing CO_2 in post-combustion plants (amine scrubbing or membranes)[163] offers the simplest solution here, although the costs could be between 50-80 USD/tonne. [164]

The capture and storage of biogenic emissions could allow the pulp and paper industry to act as a potential carbon sink (Bioenergy and CCS - BECCS).[165] The annual BECCS potential in the global pulp and paper industry is estimated at 60 - 350 $MtCO_2$.[166] With capture rates through CCS of 50 % and the use of 50 % biogenic fuels, pulp production could thus become climate-neutral. Furthermore, the CO_2 captured in this way could also be used in the production of other CO_2 -neutral raw materials or biofuels. For example, the production of starch, which is needed in the manufacture of paper, could be made from the captured CO_2.[167] Factors influencing the future development of CCUS in the

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[163] Cf. Andritz, 2022.
[164] Cf. Furszyfer Del Rio et al., 2022.
[165] Cf. Moya & Pavel, 2018.
[166] Cf. Kuparinen et al., 2019; Furszyfer Del Rio et al., 2022.
[167] Cf. Cai et al., 2021.

paper industry are, in addition to the framework for pricing CO_2 emissions, the development of concrete applications and the transport and storage infrastructure for CO_2.

Net Zero in the pulp and paper industry

The reduction and possibly complete avoidance of CO_2 emissions in the production of pulp and paper requires an interplay of all the possibilities described above. Figure 51 shows a projection of the Confederation of European Paper Industries (Cepi) regarding emission reduction in the European paper industry from 2011. Different technologies and solutions play a role and must be used in combination.

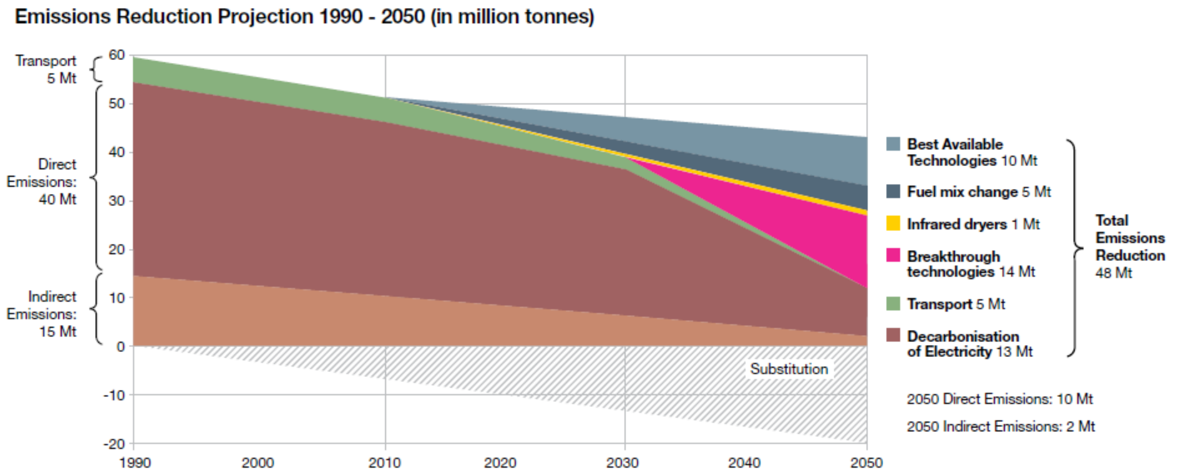

Figure 51 : Emission reduction pathway in the European pulp and paper industry.

Source: Cepi, 2011.

The application of best available technologies in all areas of the manufacturing process (CHP, waste heat recovery, energy efficiency, etc.) can provide a 21 $ reduction in emissions compared to 2010. Changes in the fuel mix towards biogenic materials, energy recovery from paper sludge and black liquor gasification as well as novel drying technologies can contribute to a further reduction of 13 %. Completely new technologies need to account for about 30 % of the GHG saved. CCUS is considered one of the "breakthrough technologies" and is necessary for complete decarbonisation or even as a sink in the pulp and paper industry. Biofuel production for wood transport accounts for 10 % of the savings. Increased electrification combined with the use of low-CO_2 grid electricity also plays a prominent role in the decarbonisation process with 27 %. Nevertheless, this emissions pathway still leaves 12 $MtCO_2$ of residual emissions in 2050. According to Cepi, the substitution of CO_2 -intensive building materials such as cement and steel with wood fibre-based building materials plays a balance sheet role on the path to Net Zero.

3.2.4.4 Application examples

As the pulp and paper industry is very heterogeneous and contains many process steps, three different application examples are considered below.

Hydrogen for power and heat generation[168]

The use of low-carbon hydrogen as a fuel can also contribute to decarbonisation in the paper industry. One application example is the conversion of a Siemens SGT-400 natural gas turbine at the French paper manufacturer Smurfit Kappa PRF in Saillat-sur-Vienne to run on pure hydrogen. The paper mill can use both the electricity and the process heat from the 12 MW turbine. The HYFLEXPOWER project is supported by a consortium of Siemens Gas and Power, Engie Solutions, Centrax, Arttic, the German Aerospace Centre (DLR) and four European universities. During two demonstration campaigns, the plant will run on a mixture of natural gas and hydrogen, with the ultimate goal of operating on up to 100 % hydrogen. The overall goal of the HYFLEXPOWER project is to test a fully green, hydrogen-based energy supply for a completely carbon-free energy mix. This would save up to 65,000 tons of CO_2 per year in base load operation. The total budget of the project is almost €15.2 million, of which €10.5 million is fully contributed by the European Union under the Horizon 2020 programme. The project, which officially started on 1 May 2020, will last 4 years and is divided into several phases:

- May 2020: Conclusion of the contract and start of technical development.
- 2021: Installation of the hydrogen production, storage and supply system at the pilot demonstration site.
- 2022: Installation of the gas turbine for natural gas-hydrogen mixtures and first demonstration of the advanced pilot plant concept.
- 2023: Pilot demonstration with up to 100 % hydrogen for carbon-free energy production from stored surplus renewable energy.

Process optimisation in paper production[169]

The forward-looking production line 8 of Voith and Koehler Paper in Kehl (Germany) is intensifying process optimisation with a focus on decarbonisation. Central to this is the further optimisation of the energy efficiency of the plants. As part of the partnership, the Voith-Koehler team is analysing alternative energy sources that can serve as future heat sources. Fossil energy sources are to be replaced by sustainable, CO_2 -neutral alternatives and the production lines converted accordingly. In

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[168] Cf. Paper First, 2020.

[169] Cf. Pulp and Paper Canada, 2022.

addition, an electrified dryer section and heat pumps offer further opportunities to increase efficiency and recover energy. The biogas obtained from the anaerobic wastewater post-treatment can also contribute to decarbonising the process. The entire production line 8 is powered exclusively by green electricity from the Schluchsee hydroelectric power plant, enabling Koehler Papier to save 45,000 tonnes of CO_2 annually.

Since the delivery of the Voith line in 2019, the 150-metre-long plant has been producing sustainable packaging paper at a capacity of 1,500 meters per minute. The heart of the plant is a Yankee cylinder with a diameter of over 7.3 meters. Coating takes place through a contactless and gentle drying process with high thermal efficiency and heat recovery.

Figure 52: Production line 8 of the paper mill in Kehl.

Source: Pulp and Paper Canada, 2022.

Biogas production in an anaerobic reactor[170]

The Julius Schulte Trebsen paper mill commissioned an anaerobic bioreactor at its factory in Saxony at the end of 2018. The mill produces 220,000 tonnes of corrugated base paper annually. The new reactor makes both the treatment of water more efficient and cleaner and the yield of biogas produced from the paper mill's wastewater higher. The anaerobic reactor cost 1.6 million euros, is 27 meters high and contains over 1300 m^3.

The previous reactor fed the produced gas directly to two cogeneration units at the factory. With the new reactor and new upgrading equipment, the biogas now reaches natural gas quality and is fed into the local gas grid of Mitteldeutsche Netzgesellschaft Gas. The biogas produced mathematically covers the annual demand of 5,000 single-family homes.

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[170] Cf. LVZ, 2018.

Figure 53: Anaerobic reactor at the Julius Schulte Trebsen paper mill.

Source: LVZ, 2018.

3.2.4.5 Developmental relevance

Like Figure 38 and Figure 39 show, it can be assumed that production and consumption of paper will increase in emerging and developing countries. The share of European or North American production, on the other hand, will decrease. Economic upswings in Asia, Africa and South America can also lead to an increase in paper consumption per inhabitant in the respective countries to the level of the industrialised countries (cf. Figure 54).

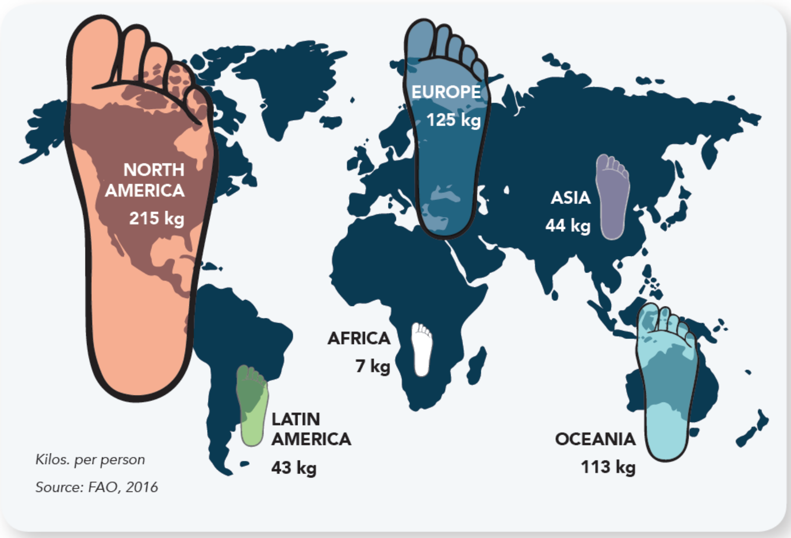

Figure 54 : Paper consumption per inhabitant in different world regions 2016.

Source: EPN, 2018.

Therefore, it can be assumed that plants in Asia will continue to account for a high share of global pulp and paper production. The use of sustainably sourced biomass instead of coal (cf. Figure 49) as fuel and the recovery of energy and raw materials can play a major role in reducing emissions.

Here, experience with the best available technologies from European and German companies can play a major role.

The production of paper is a complex process with many different process steps and also different technological designs. Increasing resource efficiency and creating synergies between the paper industry and other industries (see paragraph on biorefineries) is necessary for extensive decarbonisation. Due to the high complexity, the different raw materials and fuels, as well as the possibility of a circular economy, the pulp and paper industry offers good conditions for the dissemination of technical solutions, industrial policy incentive schemes and the development of new business models from industrialised countries to the global South. Figure 55 provides a possible framework for the elaboration of development policy strategies.

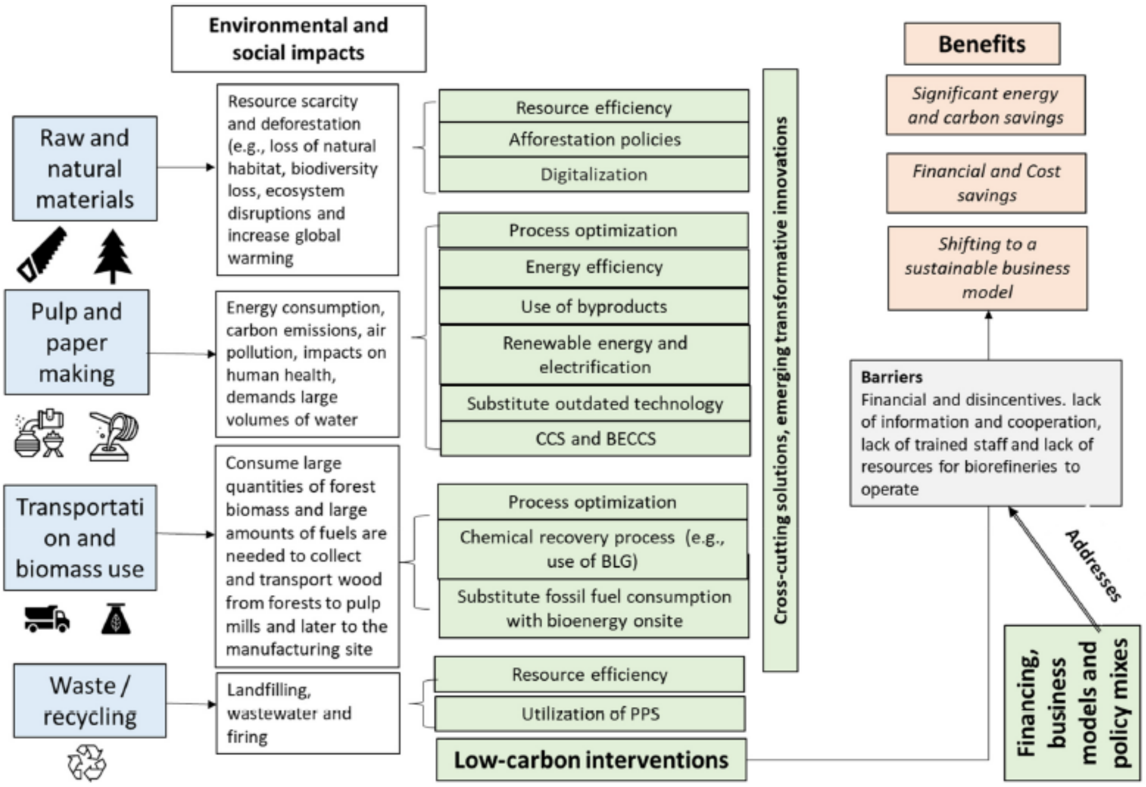

Figure 55 : The socio-technical system of the pulp and paper industry.

Source: Furszyfer Del Rio et al., 2022.

Annexes to Chapter 3.2

Annex 1: List of pilot, industrial scale and demo projects in the field of low-carbon steel production

Company	Location	Specific technology	Hydrogen type
Aço Verde do Brazil (AVB)	Maranhão state	Bio-charcoal BF	N/A
Algoma Steel	Sault Ste. Marie	BF/BOF to scrap-EAF conversion	N/A
ArcelorMittal	Ghent	NG-DR --> H-DR & EAF	Green electrolytic
ArcelorMittal	Hamilton	NG-DR --> H-DR & EAF	Green electrolytic
ArcelorMittal	Dunkirk	H-DR+EAF & CCS	Blue
ArcelorMittal	Bremen	Hydrogen production (green hydrogen)	Green electrolytic
ArcelorMittal	Bremen	NG-DR --> H-DR	Green electrolytic
ArcelorMittal	North Sea (Dutch region)	Hydrogen production (green hydrogen)	Green electrolytic
ArcelorMittal	Gijon	H-DR & EAF	Green electrolytic
ArcelorMittal	Sestao	Hybrid EAF	N/A
British Steel	Humber region	hydrogen production (blue hydrogen with carbon capture and offshore storage)	Blue
Enagas	Asturias	hydrogen production (green hydrogen)	Green electrolytic
Fortescue Metals	Pilbara	H-DR	Green electrolytic
H_2 Green Steel	Svartbyn	H-DR	Green electrolytic
HBIS	Hebei province	NG-DR (H_2 -enriched)	N/A
Liberty Steel	Whyalla	NG-DR --> H-DR	Green electrolytic
Liberty Steel	Dunkirk	NG-DR --> H-DR	Green electrolytic
Liberty Steel	Galati	NG-DR --> H-DR	Not stated
LKAB	Kiruna, Malmberget, Svappavaara	H-DR (only ironmaking)	Green electrolytic
Metalloinvest	Kursk region	NG-DR --> H-DR	Not stated
POSCO	N/A	Hydrogen production (green hydrogen)	Green electrolytic
POSCO	N/A	H-DR (based on FINEX)	Not stated
SSAB	Raahe	BF/BOF to scrap-EAF conversion	N/A
SSAB	Oxelösund	BF/BOF to scrap-EAF conversion	N/A
Tata Steel	Ijmuiden	H-DR	Not stated

Tata Steel	Ijmuiden	Hydrogen production (green hydrogen)	Green electrolytic
Tenaris	Dalmine	Hydrogen production (green hydrogen)	Green electrolytic
Thyssenkrupp	Duisburg	NG-DR --> H-DR	Green electrolytic
Thyssenkrupp	Duisburg	Hydrogen production (green hydrogen)	Green electrolytic
Thyssenkrupp	Duisburg (location of hydrogen use)	Hydrogen production (blue hydrogen with carbon capture and offshore storage)	Blue
H_2 Green Steel	TBC	H-DR	Green electrolytic
ArcelorMittal	Fos-sur-Mer	BF/BOF to scrap-EAF conversion	N/A
ArcelorMittal	Troll field	CCS	N/A
Baosteel	Zhanjiang Economic and Technological Zone	ENERGION DR	Not stated
ArcelorMittal	Ghent	CCU - Carbalyst	N/A

Table 7: List of low-carbon industry measures[171] Steel projects.

Source: Industry Transition, 2022.

Company	Location	Specific technology	Hydrogen type
ArcelorMittal	Dunkirk	CCS	N/A
ArcelorMittal	Maizières-lès-Metz	Electrowinning	N/A
ArcelorMittal	Eisenhüttenstadt	H-DR	Green electrolytic
Compañia Siderúrgica Huachipato SA	Hualpén	H-DR	N/A
SSAB	Luleå	H-DR	Green electrolytic
Tata Steel	Ijmuiden	Smelting reduction	N/A
Voestalpine	Donawitz	H-DR	Not stated
Voestalpine	Donawitz	Plasma smelting reduction	N/A
Voestalpine	Linz	Hydrogen production (green hydrogen through PEM electrolysis)	Green electrolytic

Table 8: List of pilot projects in the field of low-carbon steel production.

Source: Industry Transition, 2022.

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[171] Full-Scale

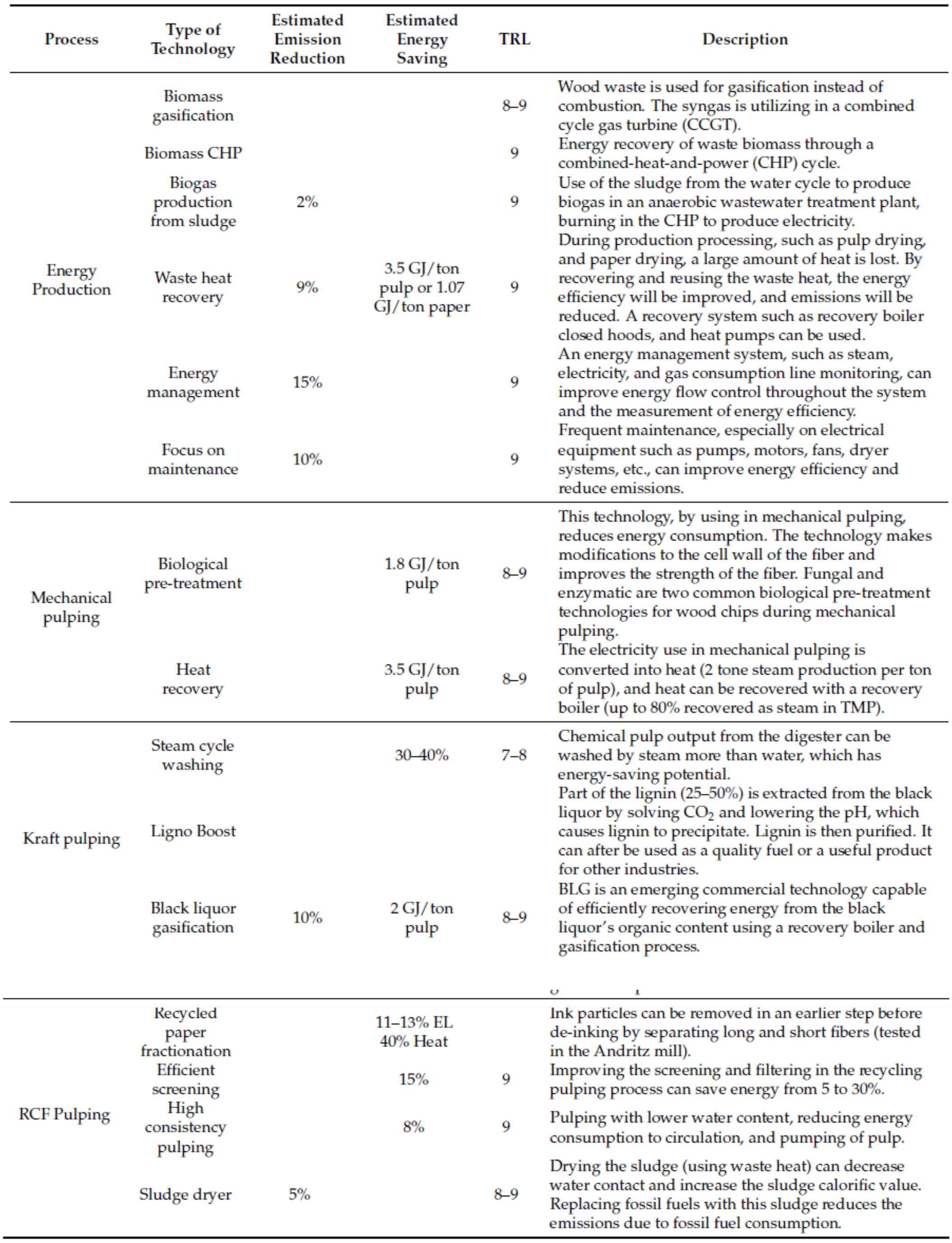
Company	Location	Specific technology	Hydrogen type
ArcelorMittal	Hamburg	H-DR (waste gas recovery) + Pressure swing adsorption	Grey
Boston Metal	Boston	MOE (molten oxide electrolysis)	N/A
Salzgitter	Salzgitter	NG-DR --> H-DR	Not stated
Salzgitter	Salzgitter	hydrogen production (green hydrogen through SOEC electrolysis)	Green electrolytic
Salzgitter	Salzgitter	hydrogen production (green hydrogen through PEM electrolysis, wind energy powered)	Green electrolytic
SSAB	Gällivare	H-DR	Green electrolytic
POSCO	N/A	H-DR (similar to FINEX)	Not stated
Calix	N/A	H-DR & Hydrogen production (ZESTY for higher value green hot briquetted iron (HBI))	Green electrolytic

Table 9: List of demo projects in the field of low-carbon steel production.

Source: Industry Transition, 2022.

Annex 2: Detailed technical measures to reduce energy consumption and GHG emissions in the pulp and paper industry

Best available technologies - best available technologies according to[172]



Process	Type of Technology	Estimated Emission Reduction	Estimated Energy Saving	TRL	Description
Energy Production	Biomass gasification			8–9	Wood waste is used for gasification instead of combustion. The syngas is utilizing in a combined cycle gas turbine (CCGT).
	Biomass CHP			9	Energy recovery of waste biomass through a combined-heat-and-power (CHP) cycle.
	Biogas production from sludge	2%		9	Use of the sludge from the water cycle to produce biogas in an anaerobic wastewater treatment plant, burning in the CHP to produce electricity.
	Waste heat recovery	9%	3.5 GJ/ton pulp or 1.07 GJ/ton paper	9	During production processing, such as pulp drying, and paper drying, a large amount of heat is lost. By recovering and reusing the waste heat, the energy efficiency will be improved, and emissions will be reduced. A recovery system such as recovery boiler closed hoods, and heat pumps can be used.
	Energy management	15%		9	An energy management system, such as steam, electricity, and gas consumption line monitoring, can improve energy flow control throughout the system and the measurement of energy efficiency.
	Focus on maintenance	10%		9	Frequent maintenance, especially on electrical equipment such as pumps, motors, fans, dryer systems, etc., can improve energy efficiency and reduce emissions.
Mechanical pulping	Biological pre-treatment		1.8 GJ/ton pulp	8–9	This technology, by using in mechanical pulping, reduces energy consumption. The technology makes modifications to the cell wall of the fiber and improves the strength of the fiber. Fungal and enzymatic are two common biological pre-treatment technologies for wood chips during mechanical pulping.
	Heat recovery		3.5 GJ/ton pulp	8–9	The electricity use in mechanical pulping is converted into heat (2 tone steam production per ton of pulp), and heat can be recovered with a recovery boiler (up to 80% recovered as steam in TMP).
Kraft pulping	Steam cycle washing		30–40%	7–8	Chemical pulp output from the digester can be washed by steam more than water, which has energy-saving potential.
	Ligno Boost				Part of the lignin (25–50%) is extracted from the black liquor by solving CO_2 and lowering the pH, which causes lignin to precipitate. Lignin is then purified. It can after be used as a quality fuel or a useful product for other industries.
	Black liquor gasification	10%	2 GJ/ton pulp	8–9	BLG is an emerging commercial technology capable of efficiently recovering energy from the black liquor's organic content using a recovery boiler and gasification process.
RCF Pulping	Recycled paper fractionation		11–13% EL 40% Heat		Ink particles can be removed in an earlier step before de-inking by separating long and short fibers (tested in the Andritz mill).
	Efficient screening		15%	9	Improving the screening and filtering in the recycling pulping process can save energy from 5 to 30%.
	High consistency pulping		8%	9	Pulping with lower water content, reducing energy consumption to circulation, and pumping of pulp.
	Sludge dryer	5%		8–9	Drying the sludge (using waste heat) can decrease water contact and increase the sludge calorific value. Replacing fossil fuels with this sludge reduces the emissions due to fossil fuel consumption.

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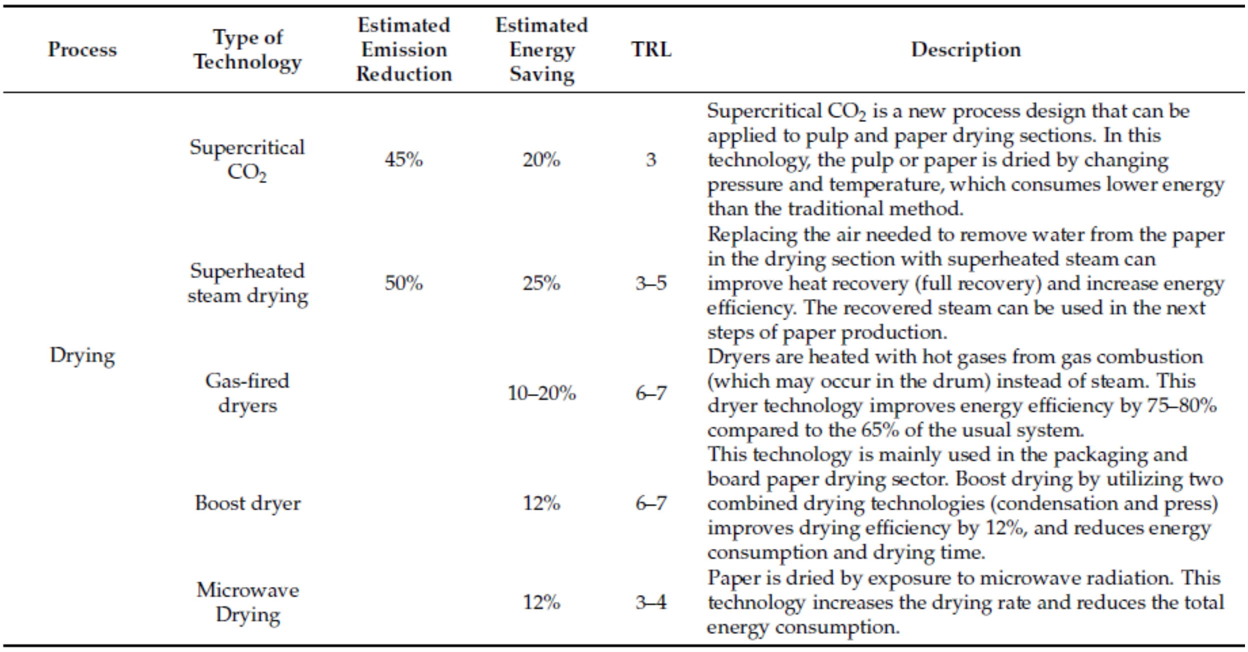
[172] Cf. Mobarakeh et al., 2021.

Process	Type of Technology	Estimated Emission Reduction	Estimated Energy Saving	TRL	Description
Paper Machine	Closed hood	13%	45% EL	9	The use of a closed hood (instead of an open or semi-open one) over the paper machine reduces energy consumption and CO_2 emission.
	Transport membrane Condenser				Energy recovery system for the low-temperature exhaust heat from the paper drying section using a ceramic membrane tube.
	Laser Ultrasonic Stiffness Sensor		3%		Sensor to measure stiffness, allowing real-time control of production. This technology reduces energy and raw material consumption.
Forming	Steam box	5%	5%		Steam box preheats the water used to form the paper, improve dewatering efficiency, and allowing higher dry contents to be attained in the press section.
	High consistency forming	3%	8% EL	7	Pulp enters the forming section with smaller water content (3% fibers). Suitable for low weight grades such as tissue.
	Dry sheet forming	42%	50%	7	Use of turbulent air in place of water as the paper carrier, meaning that there is no water added to the dry pulp, reducing energy for drying
Press section	Hot pressing	8%	0.61 GJ/ton paper	7–8	Hot pressing increases water removal in the press section, reducing the heat needs in the drying section.
	Displacement Pressing		30%		Combination of mechanical and air pressure, increasing solids content by up to 60%.
Drying	Impulse drying of paper	20%	0.44 GJ/ton paper	7	Impulse drying uses the heat and pressure in mechanical dewatering before the drying section. It can reduce the water content and increase the solid content by up to 65%.
	Condebelt dryers		1.6 GJ_{steam} & 20 KWh EL/ton paper	7–8	In this technology, the paper is dried between two steel belts in high pressure (max. 10 bar) conditions. The temperature for drying is max. 180 °C, and the steam and electricity consumption can be reduced.

Innovative technologies

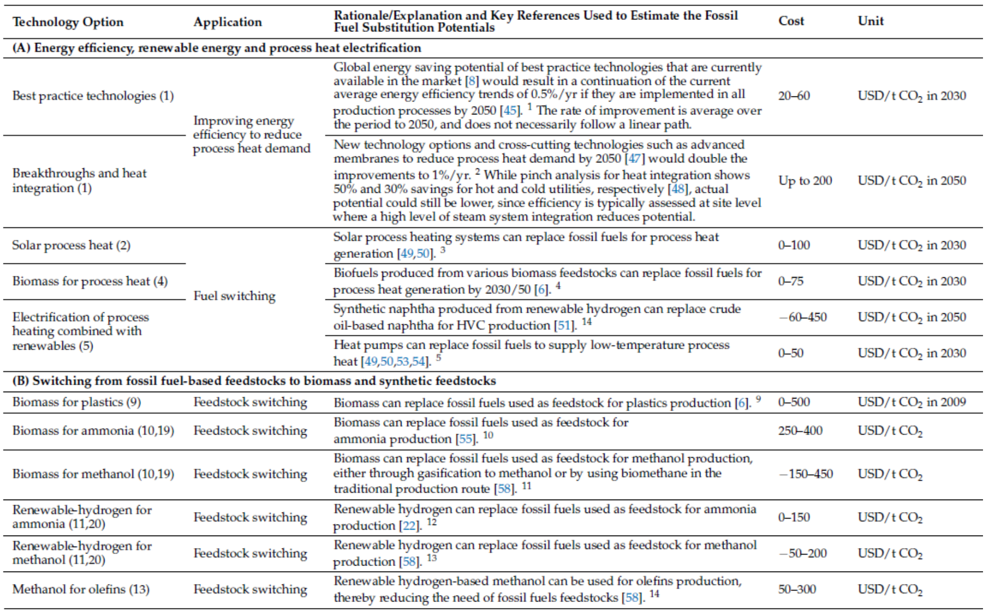
Process	Type of Technology	Estimated Emission Reduction	Estimated Energy Saving	TRL	Description
Pre-treatment technology	Microwave pre-treatment		25%	6–8	By changing the cellular microstructure of wood, this technology increases the chemical component's permeability to the chips. It applies to chemical pulping and can reduce energy consumption and the amount of chemical needed.
	Chemical pre-treatment with oxalic acid				The technology is used in mechanical pulping and can improve fibers' separation rate (defibration), and refines efficiency by using chemical components such as oxalic acid.
	Hemicellulose extraction before chemical pulping				Extraction of hemicellulose before pulping decreases alkali consumption, improves the energy efficiency, and increases the production capacity of kraft pulping

Process	Type of Technology	Estimated Emission Reduction	Estimated Energy Saving	TRL	Description
Steam production	Use of Hydrogen as a fuel			7–8	Using hydrogen (purchase (especially green H_2) or on-site production by electrolysis) instead of natural gas can significantly reduce CO_2 emissions.
	Direct electric heating			7–8	By replace fossil fuels with electricity and using an electric boiler instead of a fossil fuel boiler (natural gas boiler) to generate heat (steam) demand, fossil fuel emissions could be eliminated. If the electricity is supplied with renewable sources, net-zero emissions could be reachable.
	Heat pump recovering waste heat			6–7	By recovering the waste heat (at low temperature <100 °C) from the process using a heat pump and converting it into medium-temperature heat (max. 160 °C) (Direct information from heat pump manufacturer), energy efficiency would improve, and fossil fuel emissions could be drastically reduced.
	Carbon capture and storage			6	It may be applied through pre-combustion (associated with black liquor gasification), post-combustion (which is the more straightforward technology), or oxy-combustion technologies
Pulp Production	Deep eutectic solvents (DES)	20%	40%	3	DES are produced naturally by plants and can break down wood and selectively extract cellulose fibers required in the papermaking process. This technology could replace the traditional chemical and mechanical pulping techniques by enabling dissolving the wood and extracting lignin, hemicellulose, and cellulose at low temperatures and atmospheric pressure. Deep eutectic solvent could be applied to pulp production from both wood and recovered paper with minimal energy consumption and CO_2 emissions.
	Utilization of green liquor		25%	7–8	Pre-cooking of wood in green liquor (20–30% of the green liquor) without the lime reaction, reducing energy consumption, lime kiln load, increasing pulp yield, and bleachability.
	Membrane concentration of black liquor		36%	6–7	Partial replacement of the evaporation of black liquor by membrane concentration, reducing the thermal energy needed.
Paper Production	Functional surface			8–9	This technology aims to reduce the weight of paper without impacting its quality or structure (reducing the amount of material by 30% per square meter). Lighter weight paper needs less energy (steam and electricity) for drying, pumping, and transporting.
	New fibrous fillers		25%	5–6	Wood fibers are partially replaced by fibrous filters (based on calcium and silica), which increase the solid contact of the paper web and then reduces the energy required for the drying section.
Forming	Flash Condensing	50%	20%	3–5	The concept of this technology is to produce waterless paper using high turbulent steam combined with dry fibers. The technology can be applied to any kind of pulp (chemical, TMP, RCF) and reduces energy consumption and fossil fuel CO_2 emissions.
	Dry pulp for cure-formed paper	55%	25%	3	This technology produces paper without water by using two techniques: a dry pulp technique, which consists of a highly viscous solution and contains higher concentrated fibers, and a cure formed technique, which allows the formation of thin sheets.
Press Section	Displacement pressing		30%	5–6	In the press section before the paper drying, water can be removed from the web using a combination of mechanical and air pressure. This technology increases the solids content to 55%, which leads to a reduction in energy consumption in the drying area.

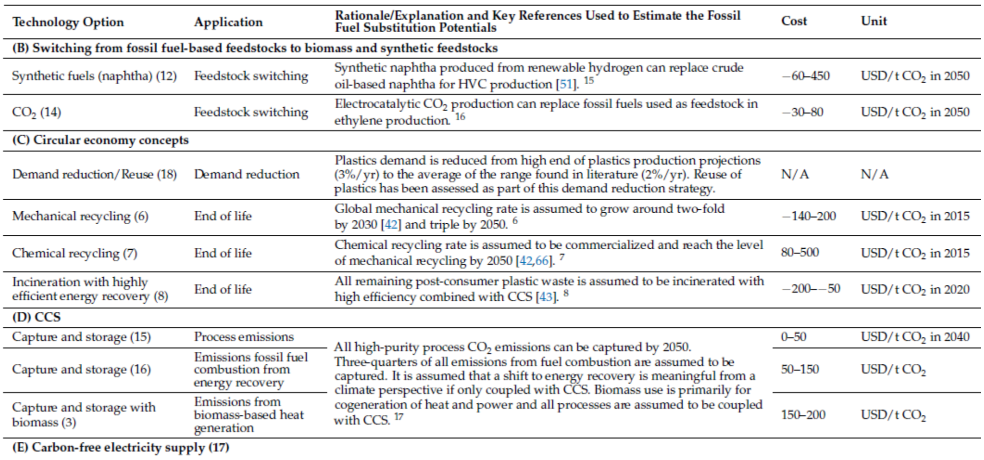


Process	Type of Technology	Estimated Emission Reduction	Estimated Energy Saving	TRL	Description
Drying	Supercritical CO_2	45%	20%	3	Supercritical CO_2 is a new process design that can be applied to pulp and paper drying sections. In this technology, the pulp or paper is dried by changing pressure and temperature, which consumes lower energy than the traditional method.
	Superheated steam drying	50%	25%	3–5	Replacing the air needed to remove water from the paper in the drying section with superheated steam can improve heat recovery (full recovery) and increase energy efficiency. The recovered steam can be used in the next steps of paper production.
	Gas-fired dryers		10–20%	6–7	Dryers are heated with hot gases from gas combustion (which may occur in the drum) instead of steam. This dryer technology improves energy efficiency by 75–80% compared to the 65% of the usual system.
	Boost dryer		12%	6–7	This technology is mainly used in the packaging and board paper drying sector. Boost drying by utilizing two combined drying technologies (condensation and press) improves drying efficiency by 12%, and reduces energy consumption and drying time.
	Microwave Drying		12%	3–4	Paper is dried by exposure to microwave radiation. This technology increases the drying rate and reduces the total energy consumption.

Annex 3: Possible technologies and processes for GHG mitigation in the chemical industry[173]



Technology Option	Application	Rationale/Explanation and Key References Used to Estimate the Fossil Fuel Substitution Potentials	Cost	Unit
(A) Energy efficiency, renewable energy and process heat electrification				
Best practice technologies (1)	Improving energy efficiency to reduce process heat demand	Global energy saving potential of best practice technologies that are currently available in the market [8] would result in a continuation of the current average energy efficiency trends of 0.5%/yr if they are implemented in all production processes by 2050 [45]. [1] The rate of improvement is average over the period to 2050, and does not necessarily follow a linear path.	20–60	USD/t CO_2 in 2030
Breakthroughs and heat integration (1)		New technology options and cross-cutting technologies such as advanced membranes to reduce process heat demand by 2050 [47] would double the improvements to 1%/yr. [2] While pinch analysis for heat integration shows 50% and 30% savings for hot and cold utilities, respectively [48], actual potential could still be lower, since efficiency is typically assessed at site level where a high level of steam system integration reduces potential.	Up to 200	USD/t CO_2 in 2050
Solar process heat (2)	Fuel switching	Solar process heating systems can replace fossil fuels for process heat generation [49,50]. [3]	0–100	USD/t CO_2 in 2030
Biomass for process heat (4)		Biofuels produced from various biomass feedstocks can replace fossil fuels for process heat generation by 2030/50 [6]. [4]	0–75	USD/t CO_2 in 2030
Electrification of process heating combined with renewables (5)		Synthetic naphtha produced from renewable hydrogen can replace crude oil-based naphtha for HVC production [51]. [14]	−60–450	USD/t CO_2 in 2050
		Heat pumps can replace fossil fuels to supply low-temperature process heat [49,50,53,54]. [5]	0–50	USD/t CO_2 in 2030
(B) Switching from fossil fuel-based feedstocks to biomass and synthetic feedstocks				
Biomass for plastics (9)	Feedstock switching	Biomass can replace fossil fuels used as feedstock for plastics production [6]. [9]	0–500	USD/t CO_2 in 2009
Biomass for ammonia (10,19)	Feedstock switching	Biomass can replace fossil fuels used as feedstock for ammonia production [55]. [10]	250–400	USD/t CO_2
Biomass for methanol (10,19)	Feedstock switching	Biomass can replace fossil fuels used as feedstock for methanol production, either through gasification to methanol or by using biomethane in the traditional production route [58]. [11]	−150–450	USD/t CO_2
Renewable-hydrogen for ammonia (11,20)	Feedstock switching	Renewable hydrogen can replace fossil fuels used as feedstock for ammonia production [22]. [12]	0–150	USD/t CO_2
Renewable-hydrogen for methanol (11,20)	Feedstock switching	Renewable hydrogen can replace fossil fuels used as feedstock for methanol production [58]. [13]	−50–200	USD/t CO_2
Methanol for olefins (13)	Feedstock switching	Renewable hydrogen-based methanol can be used for olefins production, thereby reducing the need of fossil fuels feedstocks [58]. [14]	50–300	USD/t CO_2



Technology Option	Application	Rationale/Explanation and Key References Used to Estimate the Fossil Fuel Substitution Potentials	Cost	Unit
(B) Switching from fossil fuel-based feedstocks to biomass and synthetic feedstocks				
Synthetic fuels (naphtha) (12)	Feedstock switching	Synthetic naphtha produced from renewable hydrogen can replace crude oil-based naphtha for HVC production [51]. [15]	−60–450	USD/t CO_2 in 2050
CO_2 (14)	Feedstock switching	Electrocatalytic CO_2 production can replace fossil fuels used as feedstock in ethylene production. [16]	−30–80	USD/t CO_2 in 2050
(C) Circular economy concepts				
Demand reduction/Reuse (18)	Demand reduction	Plastics demand is reduced from high end of plastics production projections (3%/yr) to the average of the range found in literature (2%/yr). Reuse of plastics has been assessed as part of this demand reduction strategy.	N/A	N/A
Mechanical recycling (6)	End of life	Global mechanical recycling rate is assumed to grow around two-fold by 2030 [42] and triple by 2050. [6]	−140–200	USD/t CO_2 in 2015
Chemical recycling (7)	End of life	Chemical recycling rate is assumed to be commercialized and reach the level of mechanical recycling by 2050 [42,66]. [7]	80–500	USD/t CO_2 in 2015
Incineration with highly efficient energy recovery (8)	End of life	All remaining post-consumer plastic waste is assumed to be incinerated with high efficiency combined with CCS [43]. [8]	−200–−50	USD/t CO_2 in 2020
(D) CCS				
Capture and storage (15)	Process emissions	All high-purity process CO_2 emissions can be captured by 2050. Three-quarters of all emissions from fuel combustion are assumed to be captured. It is assumed that a shift to energy recovery is meaningful from a climate perspective if only coupled with CCS. Biomass use is primarily for cogeneration of heat and power and all processes are assumed to be coupled with CCS. [17]	0–50	USD/t CO_2 in 2040
Capture and storage (16)	Emissions fossil fuel combustion from energy recovery		50–150	USD/t CO_2
Capture and storage with biomass (3)	Emissions from biomass-based heat generation		150–200	USD/t CO_2
(E) Carbon-free electricity supply (17)				

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[173] Cf. Saygin & Gielen, 2021.