Contextanalyse en roadmapstudie – Vlaamse industrie koolstofcirculair en CO_2-arm

Leverbaarheid 2: Internationale positionering, status en potentieel van Vlaanderen

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Table of Contents

Table of Figures

Table of Tables

Executive Summary

Introduction

This report builds upon the 2018 study 'Towards a Flemish industrial transition framework' for the Departement omgeving of the Vlaamse Overheid. In particular, the value chains of the industrial sectors that form the focus of this report are further developed together and the technologies that can be needed for the transition to a climate neutral industrial are explored in detail. The main scope of this report are the chemicals, refining and steel industry, but other sectors will be briefly presented too together with an overview of mitigation options.

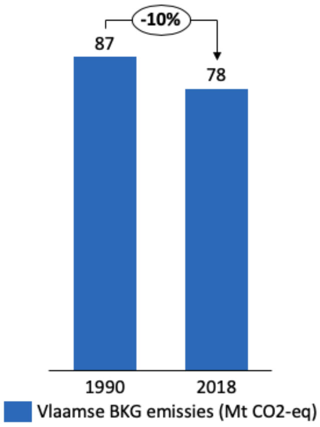
This report contains the following elements:

- A description of Flemish energy intensive industries, which are represented by the sectors covered by the EU Emissions Trading System (EU ETS). This includes overview of production, production technologies, value chains, greenhouse gas emissions, energy use and socio-economic factors such as contribution to gross value added, employment and investments in Flanders.
- An overview of technologies that can facilitate deep greenhouse gas emissions in chemicals, refining and steel, with a brief overview of options for other industrial sectors (covered by the EU ETS). For each group of technologies, the possible relevance for Flanders is presented together with possible barriers and/or opportunities.
- An overview of technological challenges based on the findings related to low-CO_2 technologies
- A short overview on possible industrial symbiosis including with sectors outside of the scope of this report
- A brief SWOT analysis on Flemish industry in relation to the transition to climate neutrality that is used to develop a general strategic view on transition pathways for Flemish industry, which will be refined with the output of the model developed and used in the overarching project.
- International comparison with neighbouring countries and overview of existing roadmaps and studies on industrial pathways to climate neutrality
- An overview of relevant policies and measures in Flanders

Profiling Flemish energy intensive industries

Flanders (still) has a rich eco-system of basic materials industry, spanning a range of diverse sectors and value chains. In general, basic materials producers such as the sectors covered in this report form the foundation of almost all materials value chains and their downstream applications in the economy.

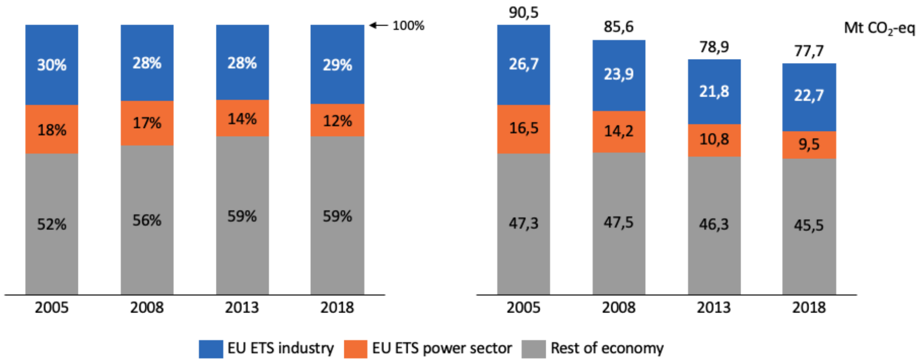
In 2018 the economy-wide GHG emissions of Flanders were 77.7 million tonnes carbon dioxide equivalent (Mt CO2-eq excl. LULUCF). Since 1990, economy-wide emissions in Flanders decreased 10% (from 86.5 Mt CO2-eq to 77.7 Mt CO2-eq).[1]



Flemish GHG emissions 1990 and 2018 (Mt CO2-eq). (Source: VMM, 2020)

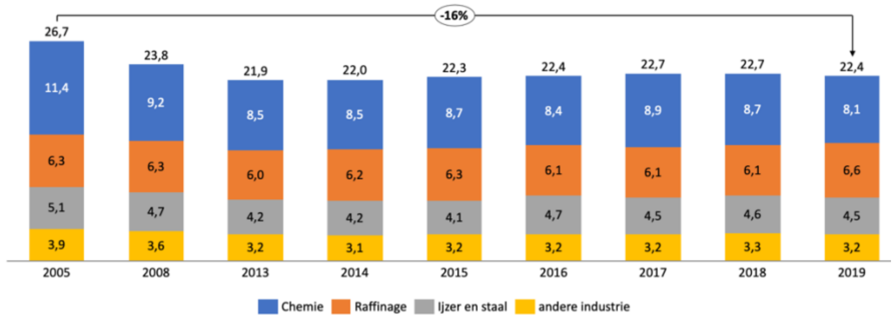
Emissions from all industrial sectors (incl. industry not covered by the EU ETS) stood at 27.9 Mt CO2-eq (in 2016) or around 36% of total emissions in 2016 a reduction of 13% compared to 1990 (from 32 Mt CO2-eq in 1990 to 27.9 Mt CO2-eq in 2016).[2] The energy intensive industries in Flanders, which fall under the scope of the EU ETS, represented 80% (22.4 out of 27.9 Mt CO2-eq.) of Flemish industrial GHG emissions in 2016. The share of Flemish industrial EU ETS sectors as part of overall Flemish industry fell from 87% to 80% between 2005 and 2016, taking into account the changes to the EU ETS scope in that period[3]. Hence around 20% of industrial emissions fall outside of the scope of the EU ETS in Flanders.

The emissions of Flemish industrial EU ETS sectors fell 16% between 2005 and 2019 (from 26.7 to 22.4 Mt CO2-eq.), taking into account the changes to the EU ETS scope in that period.



Shares of EU ETS (power and industry) emissions 2005, 2008, 2013 and 2018 [Left] % and Mt CO2 eq.[right] (Source: VMM, 2020)

[1] source: VMM, 2020]
[2] This includes both the emissions from industry covered and not covered by the EU Emissions Trading System. Source: luik mitigatie 2017 in Vlaams Overheid 2018
[3] The changes to EU ETS scope are discussed in the Vooruitgangsrapport – luik mitigatie 2017 in Vlaams Overheid 2018 p. 24

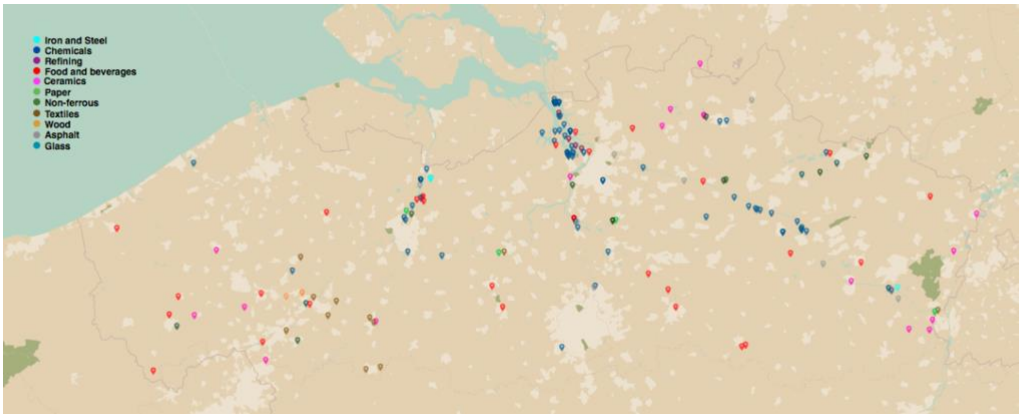


Evolution of GHG emissions under EU ETS (Mt CO2-eq.). (Source: Vlaamse Overheid, nieuwsbrief emissierechten, 2020)

The most significant emission reductions ensued in the chemicals sector (from 11.4 to 8.1 Mt CO2-eq -a reduction of 29%) and in the ceramics, non-ferrous, food and textiles industries (as a combination) (from 3.9 to 3.2 Mt CO2-eq. - a fall of 18%) over the same period.

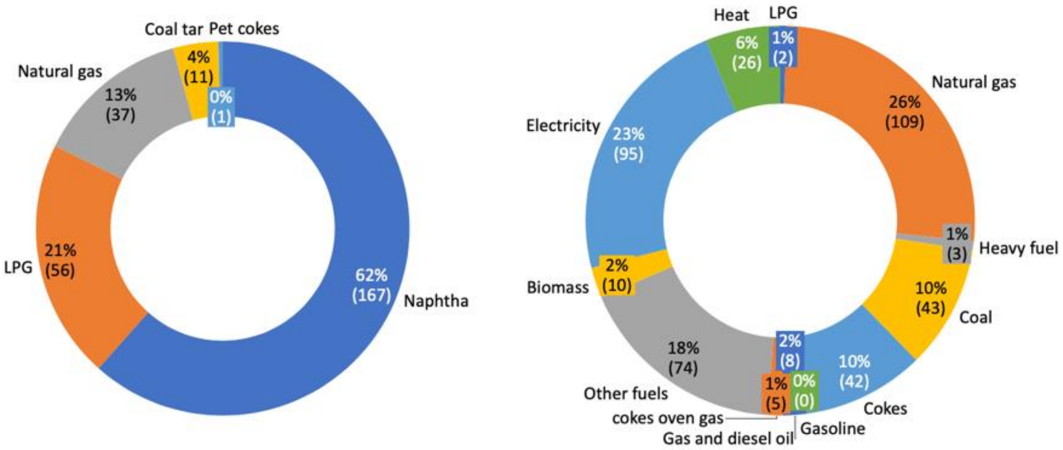
Part of the emission reductions in the latter sectors can be explained by industrial closures during the period. In particular, smaller industries such as ceramics and textiles, but also the automotive industry, were affected more significantly by those industrial closures. The sensitivity to closures indicates that an intelligent approach on industrial transformation for Flanders must be designed to avoid risking the erosion of competitiveness of the industry since closures will negatively impact welfare in Flanders and simply shift emissions to more competitive regions.

There exists a strong concentration of large industrial GHG emitters (under the EU ETS) in Flanders both on a sectoral and site basis. On a sectoral basis the combined refining, chemicals and iron and steel sectors in Flanders represented almost 86% of Flemish industrial emissions covered by the EU ETS in 2019. The top 40 of the largest industrial emitters accounted for around 90% of industrial EU ETS emissions. The top 10 largest industrial emitters accounted for around 70% of Flemish industrial EU ETS emissions. The top 40 list consists of all (large) refineries and steel producers. Most of the remaining large emitters in the list are chemicals producers. The rest include 6 food and beverages companies, 3 paper producers, 2 non-ferrous companies and one company each of ceramics, textile and glass production.



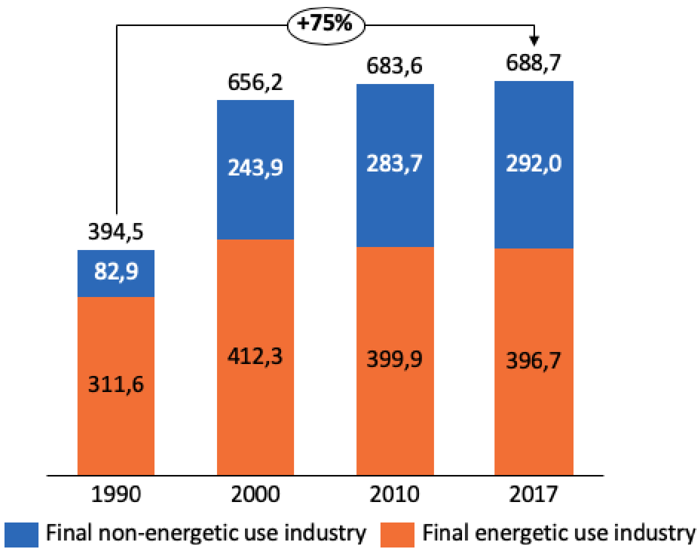
Mapping of industrial EU ETS sites in Flanders. (SourcesWyns et al., 2018b; Vlaamse Overheid, Departement Omgeving , afdeling EKG, 2017)

In 2017, the final[4] Flemish energy use was 1,245 PJ. The final energy use by industry was 396.7 PJ. The non-energetic (feedstock) use was 292 PJ or 23.5% of the Flemish total energy use. The total energy use by industry (both as feedstock and for energetic use) was 688.7 PJ or 55% of final Flemish energy use.



Industrial non-energetic use of fuels (left) and final energy use (right) by industry. % and (absolute-PJ) in 2017. (Source: Vito, 2019)

The main fuel sources (non-energetic) are naphtha (167.1 PJ), LPG (56.2 PJ) and natural gas (36.5 PJ). The main source for final energetic use are natural gas (109.2 PJ), electricity (94 PJ) and other fuels (most derived from naphtha and LPG non-energetic use) coal (42.6) and cokes (41.9 PJ).



Evolution of final energy use of Flanders in industry (1990, 2000, 2010 and 2017 (PJ) (Source: VITO, 2019)

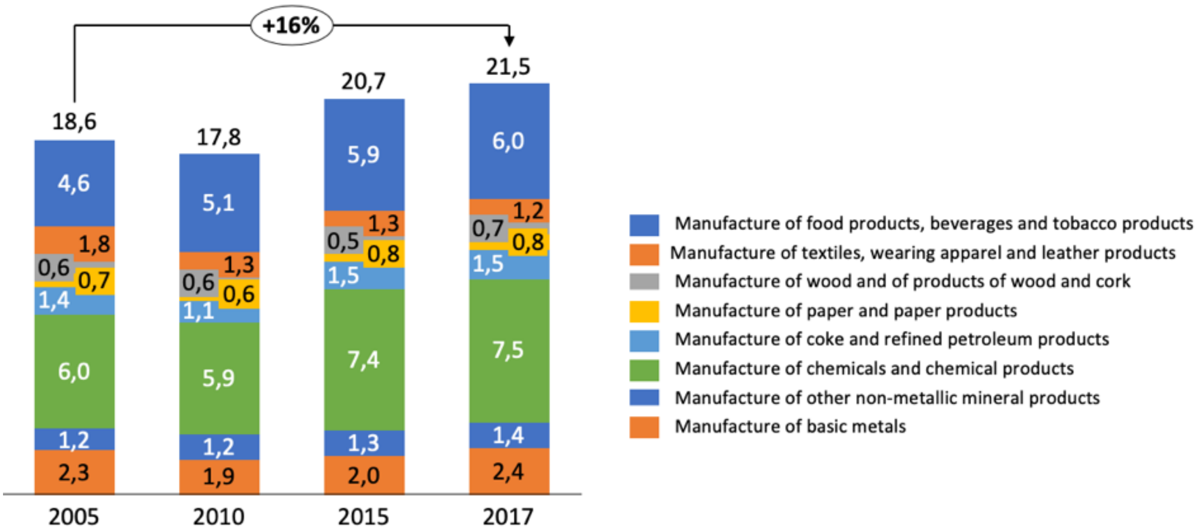
Compared to 1990, the total final energy use in Flanders went up 47% (from 852 to 1,245 PJ), with industrial energy use (incl. use as feedstock) rising 75%

[4] Excluding energy use in transformation of energy and bunkers.

(from 394.5 to 688.7 PJ) - the major contributor to this increase. In industry the non-energetic final energy use saw the biggest increase from 82.9 PJ in 1990 to 292 PJ in 2017 or an increase of 250%.

The total final energy use excluding feedstock in Flanders increased 17% (from 769 to 903 PJ) over the same period, with industrial energy use (excl. use as feedstock) rising 13% (from 312 to 385 PJ).

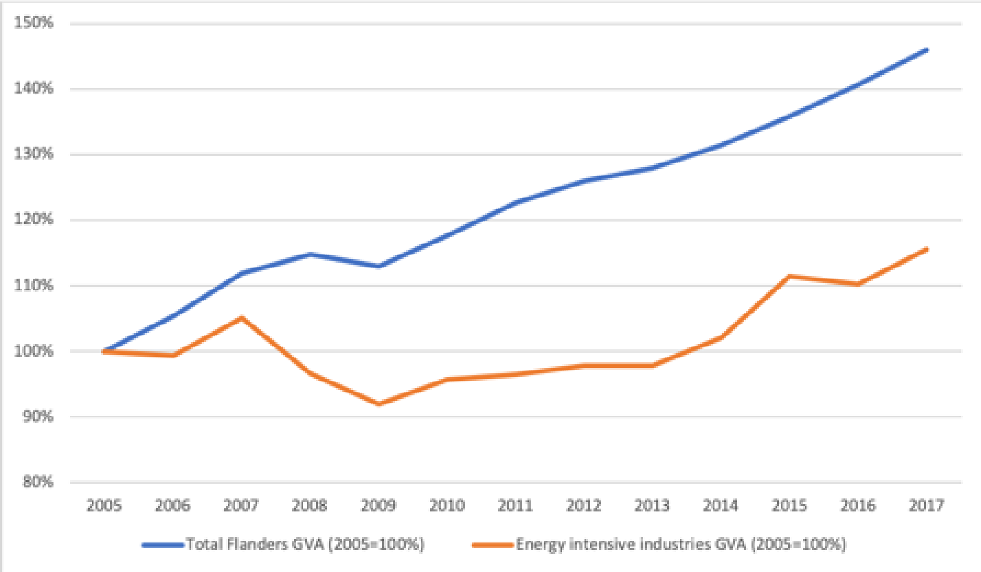
The industrial sectors chemicals and chemical products, basic metals, refining and cokes, food/drinks/tobacco, wood, paper, non-metallic minerals and textiles)[5] represented 9.1% of the Flemish GVA in 2017, in 2005 this was 10.7%. The absolute GVA for these sectors increased from EUR 18.6 Bn in 2005 to EUR 21.5 Bn in 2017, an increase of almost 16%.



GVA of the industrial sectors (absolute figure in EUR Bn) 2005-2018 (Source: NBB, n.d.)

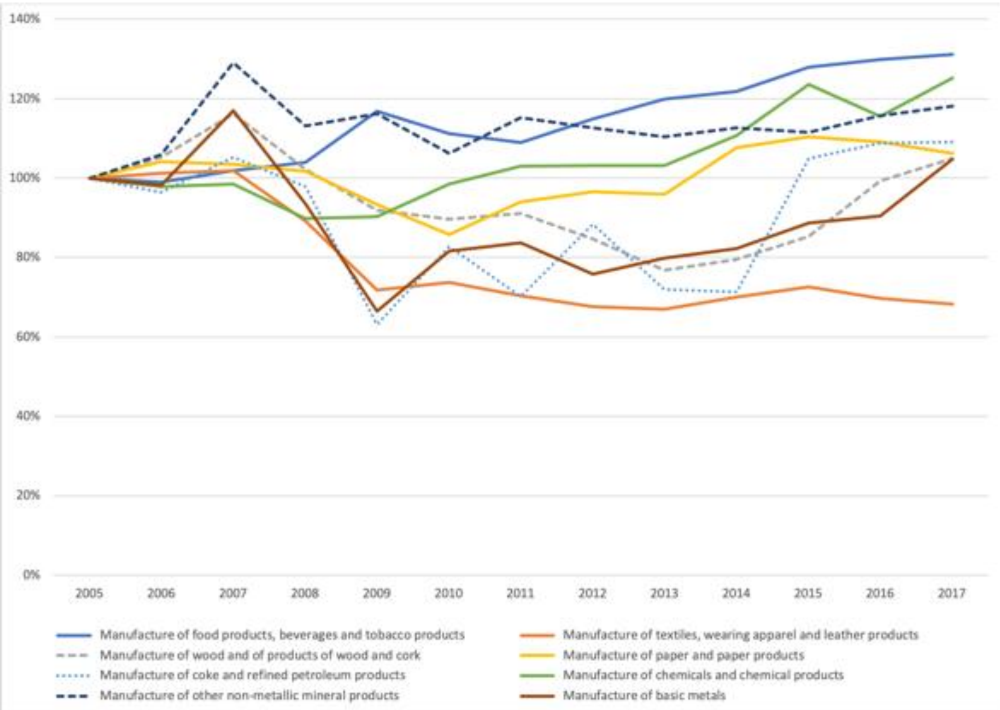
Over the same period 2005-2018 the total Flemish GVA (current prices) increased by 46% - from EUR 160 Billion (Bn) to EUR 233 Bn. This explains the declining share of these industries contribution to the Flemish economy wide GVA.

[5] Represented by NACE 10-12, 13-15, 16, 17, 19, 20, 23 and 24



Relative evolution of Flemish economy wide GVA and aggregate of Flemish energy intensive industries. (2005=100%). (Source: NBB, n.d.)

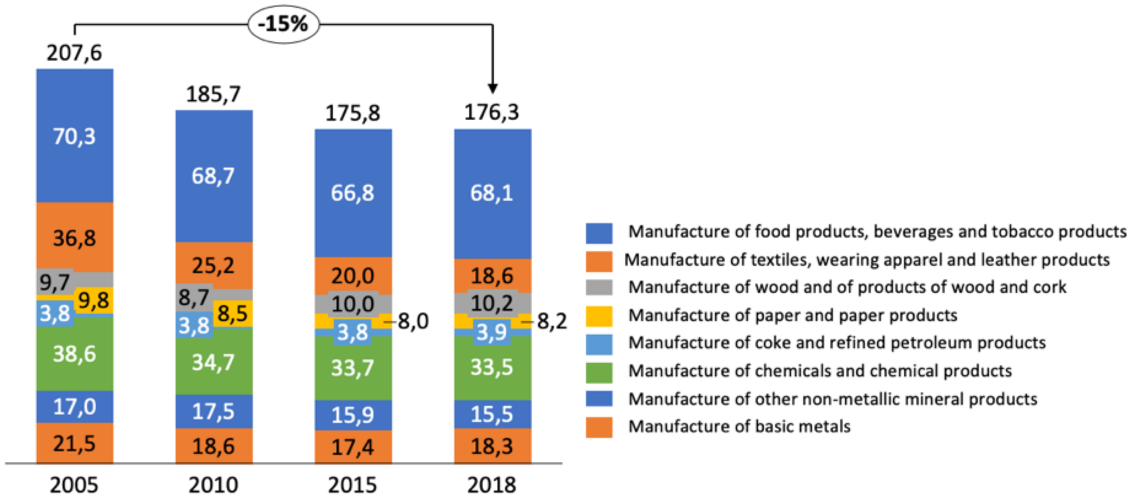
The evolution of the energy intensive industries' GVA shows the impact of the economic crisis as from 2008, with GVA recovering to pre-crisis levels only in 2013-2014.



Relative evolution of sectoral GVA (2005=100%). (Source: NBB, n.d.)

Most sectors were impacted by the crisis as from 2008 with exception of the food and beverages industry.

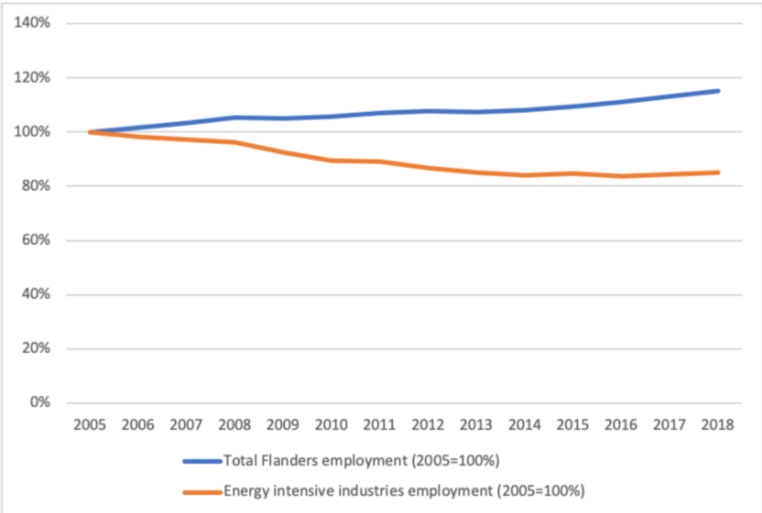
The industrial sectors (as aggregate of industrial NACE codes[6]) registered a 15% decline in employment - from 207,600 to 176,300 persons between 2005 and 2018. Indirect employment is not considered here.



Number of persons employed of the industrial sectors together (absolute figure in 1000s) 2005-2018 (Source: NBB, n.d.)

Also, the share of number of people employed by these industries compared to total Flemish employment fell from 8.5% to 6.2% between 2005 and 2018. Between 2005-2018, the total employment (number of persons) in Flanders grew 15% - from 2.45 Million (Mn) persons to 2.82 Mn persons.

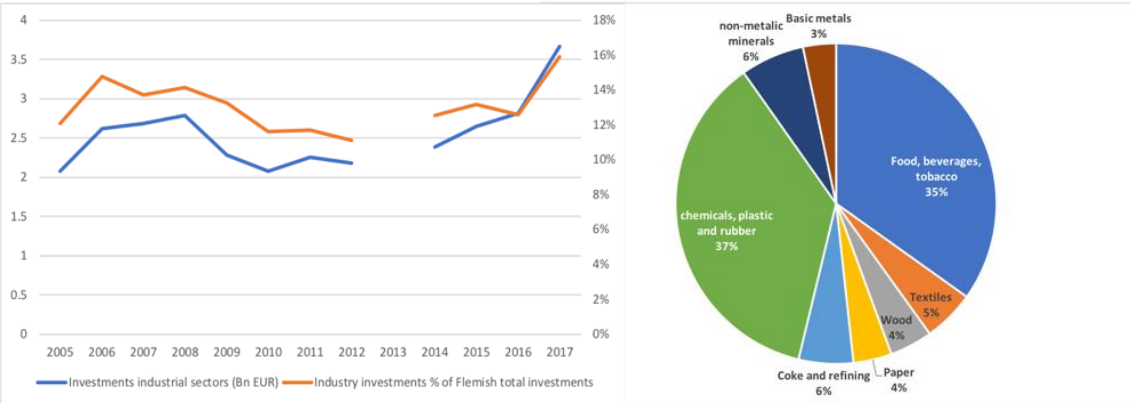
Again, there are significant differences between sectors but the downward trend in direct employment was present in almost all industries covered here[7].



Relative evolution of Flemish employment and aggregate of Flemish energy intensive industries. (2005=100%). (Source: NBB, n.d.)

[6] Represented by NACE 10-12, 13-15, 16, 17, 19, 20, 23 and 24
[7] The sectors covered here do also have an important part of subcontracted employment, but specific data was not directly available for an assessment in the context of this study.

Between 2005 and 2017, total investments in the industrial sectors covered here[8] have grown steadily from EUR 2.08 Bn to EUR 3.66 Bn. 2017 seemed to be an exceptional year as concerns investments which were EUR 800 Mn higher than the 2016 figures (EUR 2.8 Bn). Between 2005-2016 the share of industrial investments as a percentage of total investments in Flanders hovered between 12-15%. In 2017 this figure was 16%.



[Left] Energy intensive industry investments in Flanders (in EUR billions and as a percentage between 2005 and 2017 – 2013 data missing), and [Right] Share of investments in Flanders amongst energy intensive industries. (Source: NBB, n.d.)

Technologies to enable climate neutrality

Chemicals Sector

Technologies that can enable deep CO_2 reductions in (basic) chemicals production, with focus on high emission intensive HVC production, have been assessed from multiple angles:

- Breakthrough process efficiency gains, mostly via innovative catalytic processes
- Innovative electrification technologies for processes
- Bringing polymers waste back into the chemicals value chain as a replacement of fossil fuel-based feedstock
- The use of bio-based feedstock as starting point for current HVC production and/or for other bio-based polymers
- The utilisation of CO_2 emissions together with low-CO_2 hydrogen as a starting point for the HVC value chain. This includes the options and challenge to capture CO_2 from incumbent processes
- Concepts that allow deep emission reductions in heat/steam production for chemical processes through electrification, low-CO_2 fuels, system integration at industrial cluster level (applying economies of scale for carbon capture and steam production) and

[8] Aggregate of NACE 10-12, 13-15, 16, 17, 19, 20, 22, 23 and 24

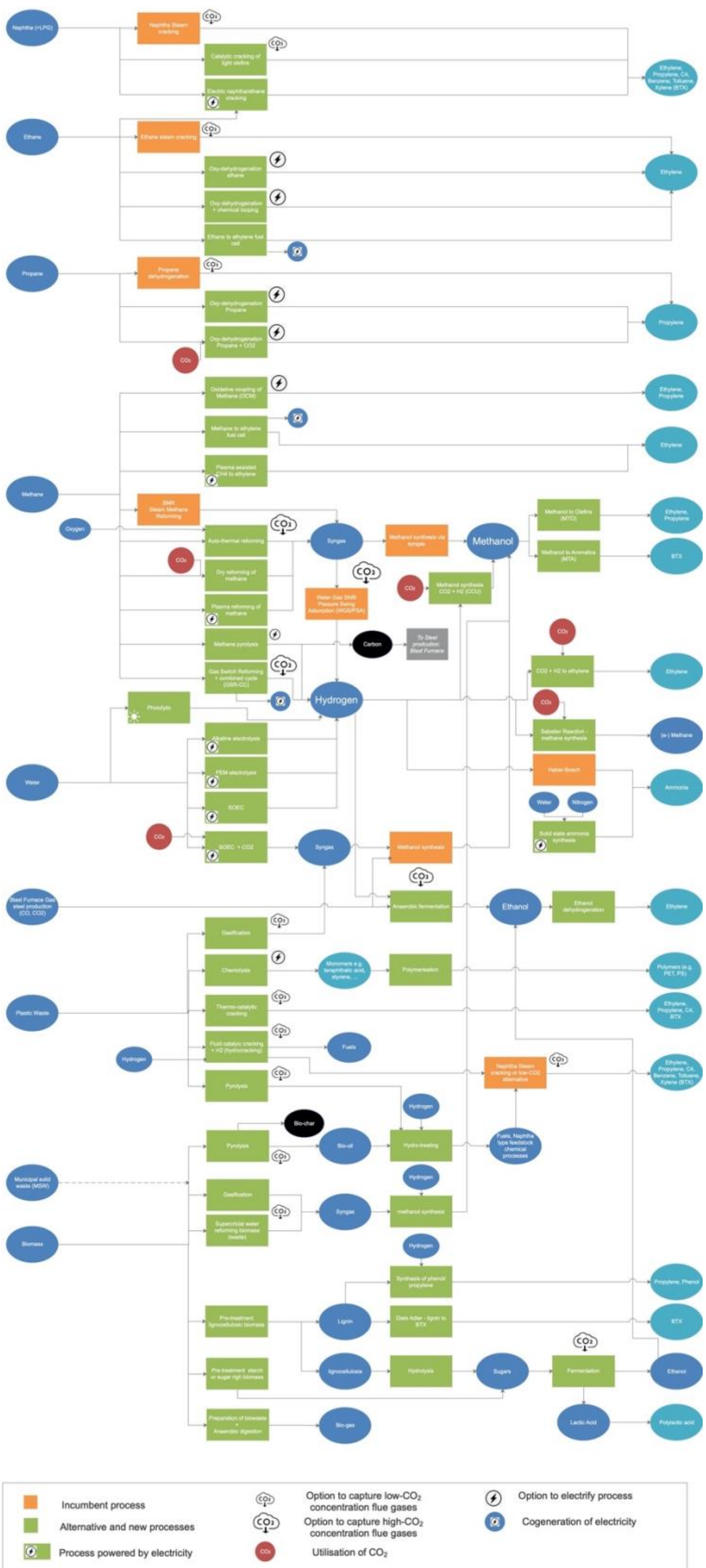
the possible enhanced symbiosis between industrial and power production (e.g. power storage and demand response).

To be successful in transforming the basic chemicals value chain towards climate neutrality these different angles or pathways should work together. In particular the emergence of new platform molecules such as methanol and (to lesser extent) ethanol which can be derived from plastic waste (gasification), biobased, via CO_2 utilisation and via classical routes with carbon capture demonstrate the concept of consistency along the different approaches.

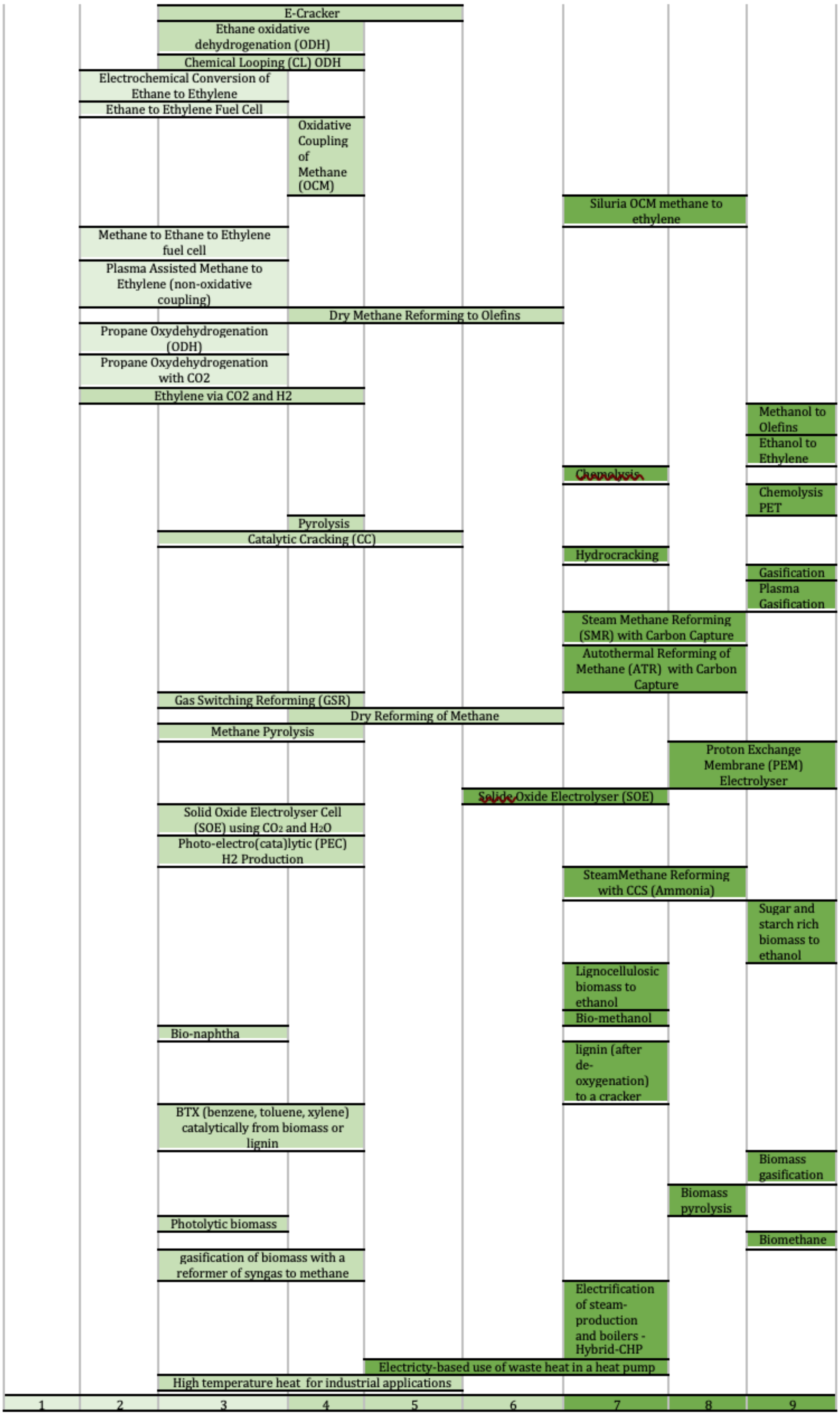
Secondly, from a perspective of timing, a smart combination of options would allow the chemicals industry to gradually move from the current modus operandi to one where carbon is more circular and remaining greenhouse gas emissions are very small. The logic here is to use the existing assets in a smart manner while building up the capacity towards a low-CO_2 production system. This implies deploying carbon capture technologies (and provide infrastructure) on the high concentration sources as soon as possible. But at the same time invest in new technologies that will become essential over time, such as (chemical) recycling of plastics (driven by both waste reduction and climate protection). Similarly, new and material efficient bio-based chemicals production has to be demonstrated either to feed the classic HVC value chain and/or towards the development of bio-based HVC- and polymer-equivalents. Preparing the infrastructure for CO_2 capture and transport and for additional hydrogen together with demonstration of promising CCU processes (e.g. methanol to olefins) sets the stage for full scale implementation of CO_2 utilisation after 2030. It is very likely that electricity and its reliable and competitively priced supply will become much more important for chemicals production. This can be either through hydrogen production, electrification of heat and carbon capture or via the promising routes that electrify large process installations (e.g. highly efficient electrical steam crackers).

It is clear that the transition of the chemicals industry will require the development of new supply chains which will replace most of the current feedstock. Therefore, it will be essential to develop the necessary logistics e.g. shipping, (inter)national pipelines (hydrogen and CO_2), increased capacity of international power transmission lines to large scale renewables and reliable biomass and plastic waste supply chains.

The flowchart below seeks to give a summary of the technology options towards the production of high value chemicals.



Pathways to HVC production



Overview of technologies considered for climate neutral chemicals (HVC) production and their Technology Readiness Levels (TRLs)

Refining Sector

The technologies and techniques for the refining industry are derived from two reports by Concawe on mitigation pathways for greenhouse gas emissions in refining and on the future of liquid fuels in the EU.

The main technological options to reduce emissions in refining of crude oil include:

- Enhancing the efficiency of processes and materials recovery
- Electrification of heating/boilers and use of low-CO_2 hydrogen
- Carbon capture and storage or utilisation

In general, there is an important potential for emission reductions linked to energy efficiency improvements, but that does not imply these all are still applicable to refineries in Flanders with the same mitigation potential. For instance, in Flanders some newer efficiency measures might already have been implemented. The activities related to efficiency improvements are:

- Continuous improvement of processes
- Large new investments in efficiency improvements
- Improved inter-unit heat integration
- Improved energy management systems
- Lowe grade heat recovery systems
- Improved recovery of hydrogen, LPG (and HVCs) from fuel gas

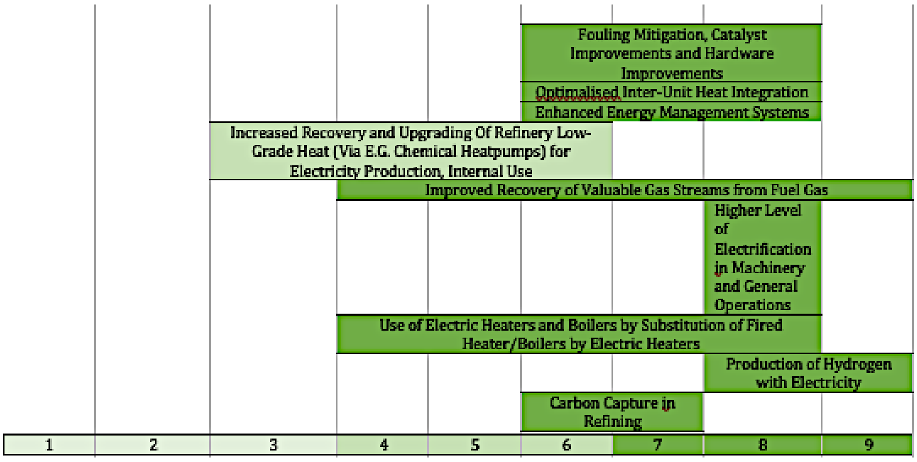
Electrification of some of the refining processes is an important option for greenhouse gas mitigation in refining. Overall, Concawe estimates that 25% emission reductions are possible by 2050[9] (vs ref. 2030) due this approach, assuming the efficiency measure mentioned before are implemented.

Electrification in refining includes the following elements:

- Higher level of electrification in machinery and general operations
- The use of electric heaters and boilers by substitution of fired heater/boilers by electric heaters
- Production of hydrogen with electricity (e.g. replacing steam methane reforming)

As seen above, energy efficiency and electrification will bring about important greenhouse gas emissions reductions but still leave more than half of the emissions in place. It is hence very likely that carbon capture will need to play an important role for deep greenhouse gas emissions in refining. Capturing CO2 in integrated refineries will be complex due to the large amount of diverse point sources. Hence integration of stacks should be considered, but this comes with complex engineering and additional costs. Furthermore, utilities will be needed to provide heat and power to carbon capture processes, adding to the costs.

[9] Compared to 2030 baseline.



Overview of technologies considered for low-CO2 refinery production and their Technology Readiness Levels (TRLs)

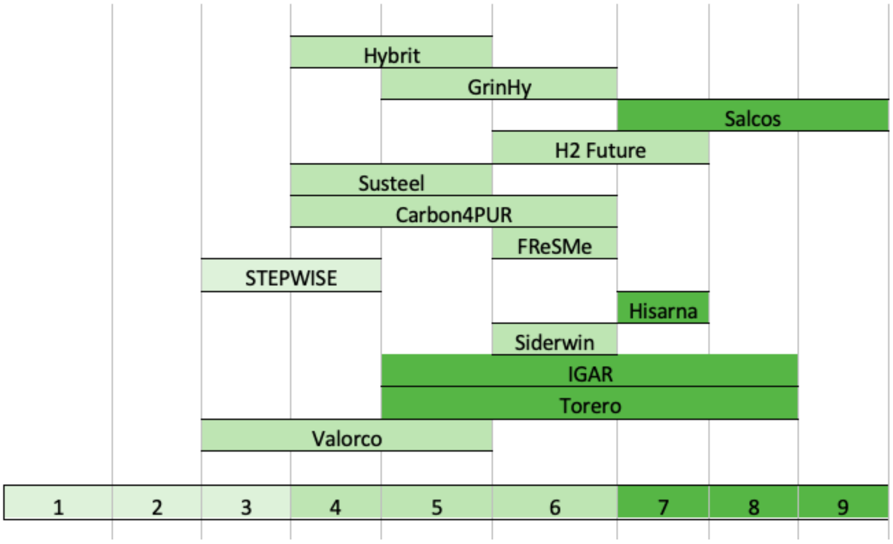
Steel Sector

For deep greenhouse gas reductions in steel production three pathways are considered by the EU steel industry:[10]

- The use of renewable electricity in basic steelmaking, including the use of hydrogen to replace carbon as reducing agent[11]
- The use of CO_2 or CO from steel production as a raw material for e.g. production of basic chemicals
- New processes and process integration in steelmaking with reduced use of carbon (incl. CCS and use of biomass and plastic waste in steelmaking)

Some of the technologies under these pathways can be combined to achieve deep greenhouse gas reductions in integrated steel mills.

[10] Ghenda, 2018
[11] Low Carbon Future, n.d.,



Overview of technologies considered for climate neutral steel production and their Technology Readiness Levels (TRLs)

The options for transition of Flemish integrated BF-BOF steelmaking are based on public presentations[12] by Arcelormittal and an interview during site visit.

The approach considered by the ArcelorMittal integrated steel plant in Flanders (Ghent) is to intelligently combine different technologies mentioned before, together with a focus of embedding steel production in the circular economy through industrial symbiosis.

The first element is the substitution of coal, used in the blast furnace for the reduction of iron ore, by a combination of:

- Use of bio-coal (Torrero project) derived from wood and other organic and non-organic waste via a torrefaction process
- Use of plastic waste and CO2 (from the blast furnace) via plasma gasification (IGAR project) delivering hydrogen and carbon monoxide to the blast furnace
- Additional hydrogen use in the blast furnace

Together this could reduce the use of coal by up to 50%.

The second element is the capturing and smart utilisation of CO, CO_2 and even nitrogen from the flue gases in steel production. This includes the conversion of CO (and CO_2) to ethanol via a fermentation process (steelanol), assisted by hydrogen to increase the yield of ethanol. The use of CO_2 and CO in methanol synthesis, also with additional hydrogen input. Possible production of naphtha via CO and CO_2 and the Fischer-Tropsch process, polyols for polyurethane, urea via the recovered nitrogen and CO_2. Finally, an interesting option to avoid emissions in agriculture would be the production of proteins that can replace animal feed via CO_2 as feedstock.

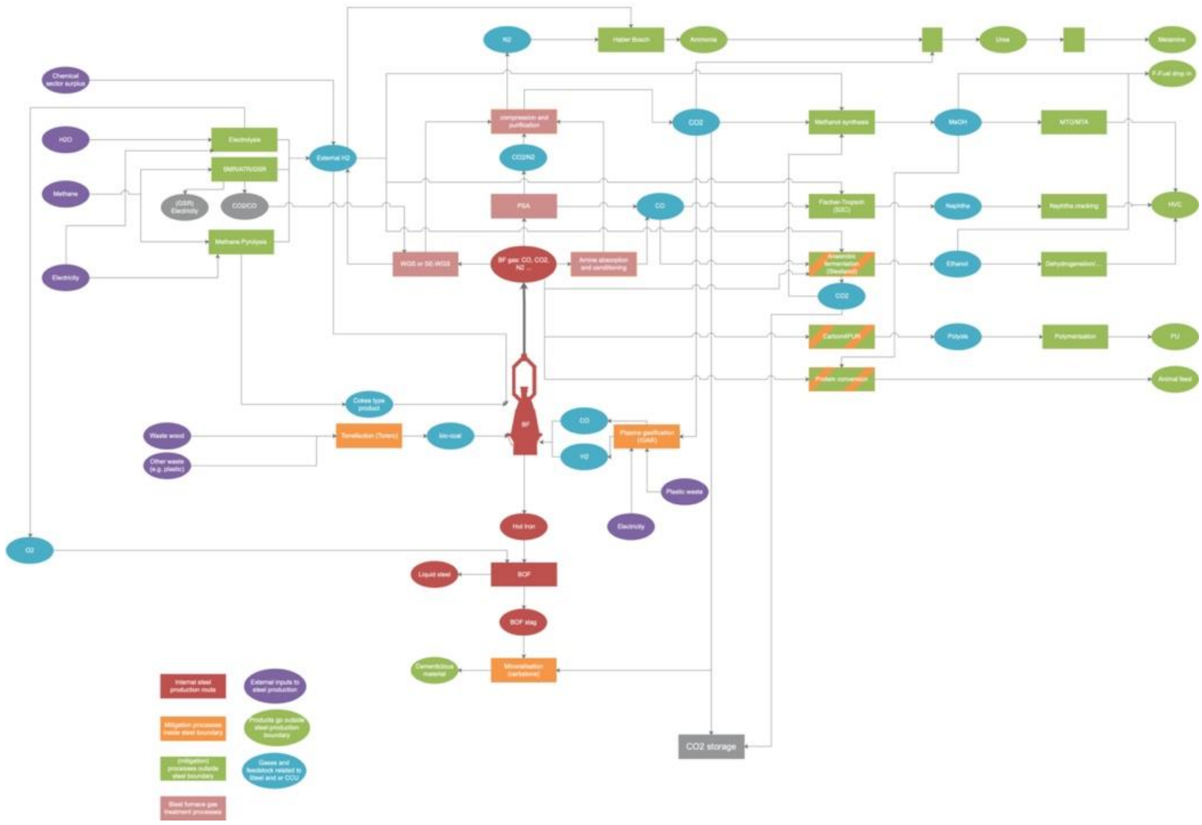
[12] De Maré, 2019

To achieve the utilisation of CO_2 an efficient CO_2 capture process will have to be deployed, something which is under development at the moment. Furthermore, the use of CO (and CO_2) would eliminate the current power production via steel waste gases. Therefore, additional electricity demand will have to be provided, including for the large amounts of hydrogen required for the CO and CO_2 utilisation processes.

Finally, the remaining CO_2 emissions in steel production and the (highly concentrated) CO_2 emissions from the steelanol process will have to be captured and stored.

All these options, when maximally deployed, together would bring result in very few remaining greenhouse gas emissions from steel production (e.g. beyond 80-90% compared to around 9 Mt CO_2 emissions today).

A result of the above-mentioned approach would lead to important symbiosis between steel production and chemicals production (e.g. methanol, ethanol to HVCs), between steel and the circular economy (through the use of bio-based and plastic waste in steel processes) and possibly between steel and food production via the production of proteins from CO_2.



Options for greenhouse reductions and utilisation of CO2 in existing BF-BOF steel production

Other industries

In general, the smaller emitting sectors such as paper, textiles, non-ferro and food production will mainly have to consider fuel switches (mostly replacing natural gas) and related technologies to achieve emission reductions, next to continued investments in energy efficiency and related technologies. This can include electrification, use of biofuels or use of e-fuels. Most of the companies in these sectors do not form part of larger industrial clusters such as Port of Antwerp, the Ghent harbour zone or the stretched zone close to the Alberkanaal. This implies that cluster strategies such as use of hydrogen, CO_2 capture and utilisation or storage or large steam network integration will not be directly at the disposal of these companies due to large infrastructure costs involved.

Electrification of heat, especially for smaller and low temperature installations could be considered on relative short term. The main bottleneck here is cost with electricity prices being much higher than natural gas on a MWh basis. Some sectors such as glass, ceramics and non-ferro require high temperature (sometimes above 1000°C) here electrification is also technically challenging with interesting options being developed (e.g. microwave assisted heating in ceramics and glass) but no mature technologies to replace fossil fuel-based burners. Further R&D into high temperature applications using electricity will be important, especially if these technologies entail important efficiency gains (to off-set part of the cost difference with natural gas).

Biomass and biofuels are already applied in some sectors such as the food and paper industry. Higher use of biomass for energetic use will require a stable and price-competitive supply chain. One option could be to redirect bio-diesel production, currently aimed at the transport sector towards (decentralised) industrial applications. This will require policy interventions at EU, national and subnational levels. Given that Flanders is an important producer of biofuels local market creation via supporting policy instruments could bring about lead markets for biofuel use in these industrial sectors.

E-fuels, discussed in detail in other chapters, can in theory relatively easy be used as alternative (e.g. e-methane which is almost identical to natural gas). However, they are not mature and produced at large scale and are expected to be more expensive at least until 2035-2040. The latter will depend on the possibility to import e-fuels (e.g. e-methanol) from areas with exceptionally low-cost renewable electricity.

Mitigation options might also be found outside the companies' perimeter. For instance, through the valorisation of low-temperature heat from the processes in the residential sector. Some of the companies in the above-mentioned sectors are located in close proximity to residential areas and can deliver excess heat (for residential hot water or heating) to this sector. This will require support by local authorities and facilitation by local infrastructure operators (e.g. intercommunales).

The circular economy and related business models will more and more find entrance in these sectors. The paper sector and non-ferrous metals industry in Flanders are already closely intertwined with recycling. Sometimes climate and circular economy policies might work against each other (e.g. recycling of paper/cardboard and metals (electronic waste) that come with combustion of other materials that cannot be recycled and hence increase greenhouse gas emissions. Future policies aimed at either circular economy and/or climate must be integrated to maximise benefits at both sides or avoid unintentional consequences. The food and beverages industry, a major user of packaging materials, will increasingly have to be involved in the circular plastics value chain. In particular with stronger links to the new (plastic) chemical recycling routes mentioned in the previous chapter on chemicals technologies. Here industrial symbiosis can become very important because chemical recycling will depend on economics of scale and a steady supply chain.

Notwithstanding all the above-mentioned options, it is likely that mitigation in these smaller industries towards climate neutrality will not be easy. As mentioned before, many companies will lack the infrastructure for or to important mitigation options such as use of hydrogen, CO_2 capture or integrated steam networks. But also, smaller companies might not have access to intra-company R&D resources and capital required for high-tech energy efficiency investments or new technologies enabling fuel switches. Therefore, it is recommended that on short notice additional policy attention should go to facilitating R&D, investments in efficient climate friendly technologies and cross-sectoral initiatives in smaller industries and companies.

R&D challenges

Based on the analysis on technology options for deep greenhouse gas reductions some general and specific recommendations can be formulated regarding the R&D challenges for industrial transition to a climate neutral economy.

The general observations on R&D challenges are:

- Many of the technologies presented are at relatively low TRL's (e.g. 3-4). It will require dedicated investments into pilot and later demonstration plants to ensure these options become available at large scale well before 2040.
- While many processes show high emission reduction potential their efficiency from an energy and materials (e.g. low yield) perspective will need to be improved significantly. This will require further investments in basic research but also the scaling up and deployment of technologies to activate technology learning curves that come with efficiency gains (and cost reductions)
- The technologies considered are often stand-alone processes. These do not reflect performance in often complex and integrated production systems. Hence, it will be important to invest in modelling and testing of system integration of new technologies. This includes the integration with energy and materials flows in industrial production systems.
- Finally, cost reductions both from the OPEX and CAPEX side will be essential to make innovative processes compete (even in the presence of a price on CO_2 emissions) with (global) incumbent technologies. Again, this will require accelerated deployment supported by (temporary) policy interventions such as contracts for difference (i.e. a subsidy to cover incremental production costs) until the technologies have matured enough.

Technology specific observations on R&D challenges include:

- Electrification of high temperature heat could prove a very efficient and climate friendly technology. However, it hasn't advanced enough for commercial deployment on short or even medium term. The challenge here is to develop processes that are at least 40-50% more efficient vis-à-vis heat via natural gas as to make up part of the cost disadvantage of electricity.

- Energy and cost-efficient (gas and liquid) separation technologies will remain important as to improve both the yield and energy needs for e.g. HVC production.
- Catalysts, both their chemical and physical design, will become even more important multi-purpose technologies due to their application in almost all low-CO2 chemicals processes (e.g. CO2 capture, synthesis of methanol, plastics recycling, …). Accelerated development of new, durable, (if possible) cheap and non-critical raw materials dependent catalysts will be crucial. Hence, investing more in dedicated laboratories that have access to advanced machine learning tools for faster validation of catalytic properties will be a no-regret R&D investment.
- Materials efficient use of biomass (i.e. focusing on highest possible HVC (or HVC equivalent) yields) should become a guiding factor in bio-based chemicals R&D. This includes development of innovative processes, but foremost the evaluation of system integration in bio-refineries which combine different biomass conversion and energy recovery technologies.
- For carbon capture the main R&D challenge is reduction of OPEX, mostly related to additional energy use for the capture process. Here the introduction of performance benchmarks (e.g. < 2 GJ/t CO_2 captured) could offer important guidance to future R&D investments.
- Given that carbon capture is likely to be a critical technology for chemicals, refining and steel production and that it would come with high additional energy needs it is essential that excess industrial heat, currently not used, is integrated with carbon capture processes. Hence, processes such as chemical heat pumps that can bring <100°C waste heat to the required temperature range for some capture processes will be essential for efficient and integrated capturing of CO_2 in existing industrial processes.
- Furthermore R&D into technologies that facilitate the symbiosis between heat and electricity will be important for large scale industrial applications. For instance, the use of industrial heat to drive more efficient high-temperature electrolysis.
- Industrial cluster level system integration of carbon capture will require additional R&D to ensure that the diverse CO_2 sources with different concentrations can be integrated cost-efficiently into a carbon capture and transport hub.
- Similarly, further R&D into the integration of (new) industrial processes in the energy system will be critical on the road to full and efficient deployment of new process technologies. For instance, advanced use of industrial demand response, options for energy storage (e.g. in materials and fuels) via industrial processes, recovery of excess heat for electricity production, …

The above-mentioned lists are by no means meant to be complete but reflect some of the main findings and concerns that followed the technology analysis in the previous chapters.

Options for industrial symbiosis

Low CO_2 technologies and pathways show an important potential for industrial symbiosis between industrial and non-industrial sectors through mutual materials, energy flows or by dual use of low-CO_2 technologies in other sectors.

Crude oil refining already has a high level of integration with petrochemicals production by producing feedstock for chemicals production or production of basic chemicals. A number of technological options for greenhouse gas mitigation in chemicals production will also be highly relevant for refining. For instance, zero CO_2 hydrogen production, use of plastic waste for production of feedstock, bio-based fuels, electrification of boilers, CCS and CO2 utilisation e.g. for production of e-fuels.

Major opportunities for deep industrial symbiosis between *steel* and chemicals production exist. From the side of steel production, the use of waste gases from cokes and iron and steel production offers the potential of feedstock for large volumes of basic chemicals production (e.g. via ethanol or methanol). Furthermore, plastic waste can be used (e.g. via plasma gasification) as reducing agent in hot iron production. Future low-CO_2 steel production will also depend on large volumes of zero-CO_2 hydrogen production (either for reduction of iron ore or for higher levels of utilisation of steel waste gases). Hence zero-CO_2 H_2 technology will also be relevant for steel producers. Methane pyrolysis, for instance, can deliver both H_2 and carbon that can be used in iron ore reduction. Finally, carbon capture technologies will play a role in future mitigation of steel sector emissions.

Part of the Flemish *food and drinks industry* already has a strong link with chemicals production either through being producers of plant-based oils or by the use of by-products in chemicals production (e.g. ethanol and citric acid). Depending on market conditions and the regulatory environment there can be a shift from biofuels towards bio-based chemicals. The food industry will be able to benefits from technological innovations that help reduce emissions from (steam) boilers e.g. electrification, biomass/biogas, fuel cells and heat pumps. Production of food and drinks can, if located close to major chemicals/steel producers, benefit from cross-company integrated steam networks and hence forego use of on-site boilers. Furthermore, the important use of plastics packaging in food and beverages production offers options of further industrial symbiosis with advanced chemicals plastic recycling via the recovery of packaging waste. Finally, advanced use of CO_2 includes the possible production of proteins which can be applied in animal feed or as meat replacement for human consumption.

Pulp and paper production, similarly to food and drinks production, will require (cost-effective) innovations with regard to heat/steam production. Heat integration with other major heat consumers is possible in theory but limited because of location of most paper/cardboard producers. On the other hand, cardboard and paper production can become a low-T heat provider to other sectors (in particular buildings sector) via heat-networks driven by waste heat from steam for paper production. Paper and cardboard producers working with recycled materials could consider technological innovations related to recovery of materials/energy from waste streams (input/output).

There is potential for interesting deeper symbiosis between *waste* treatment, recycling and incineration and the chemicals and steel industry. The waste treatment industry is seen as frontrunner in Flanders in the area of chemical recycling with potential of high level/value integration of chemical-plastic recycling in the Port of Antwerp. Similarly, the sector is a frontrunner in enabling the development of a large integrated steam network in the Port of Antwerp (Ecluse project), replacing decentral boilers and reducing emissions by economies of scale. Finally, MSW can become important feedstock for chemicals/steel production e.g. via gasification/torrefaction.

Symbiosis between the industrial and energy and in particular *power sector* is widely present, in particular through the use of large and smaller scale combined heat and power (CHP) installations. Deploying carbon capture (and utilisation and storage) to CHP installations will on short term not be straightforward and costly (due to the low CO2 concentration in CHP flue gases). However, industrial symbiosis between energy and industry will be essential towards climate neutrality due to higher electricity needs for industry (e.g. electrification of boilers, process installations, carbon capture and H_2 production). Furthermore, heat and steam demand will still be high from industry side regardless of technologies used. The following elements could be considered:

- Direct access to renewable electricity (e.g. offshore wind) not on site together with maximising on site RE deployment (limited).
- Integrating electrification of processes with variable renewable electricity through demand response and where possible storage at industrial sites/in products
- Develop efficiency electricity generation with CCS (Allam cycle) using CO_2 networks in proximity.
- Use new processes that can co-produce electricity and heat and/or products such as fuel cells
- Evaluate highest value use of biomass for energy/feedstock
- Facilitating business models for cluster level heat/steam generation and networks
- Find use for low-T/P waste heat outside of industry such as the residential sector.

Industrial cluster (e.g. port) scale industrial symbiosis will have to be strengthened using the deployment of low-CO_2 technologies, hydrogen and steam/heat and infrastructure:

- Extended steam networks with fewer large boilers generating steam. This can reduce (overall) costs of CO_2 capture given that capture technology will only have to be deployed at fewer locations and at larger scale, likely leading to (overall) cost savings. For users of steam the use of chemical heat pumps can locally assist with bringing steam from the network at higher T and or P, if required.
- A CO_2 pipeline network would offer infrastructure for captured CO_2 and hence enable investments in CO_2 capture or, at later stage, utilisation. It can be considered if supercritical CO_2 can be used as more efficient heat transfer agent vis a vis steam.
- Extended H_2 network and flexible access to the network.
- Integration with electricity production incl. renewable electricity and power production with CCS (Allam-cycle).

On a broader scale the important industrial clusters form part of a maritime linked industrial eco-system. Many if not most of the energy and materials supplied to industries such as steel, chemicals and refining arrive by ship. These logistic routes will also be important for future new supply chains (e.g. methanol). The maritime sector is expected to be essential for the industrial transition, in particular given its potential to supply the northwestern European industry with large amounts of renewable electricity via offshore wind. Wind-Europe recently estimated an economic potential of up to 6000 TWh electricity at prices below 60 EUR/MWh. This is twice the current EU electricity demand. It can hence not be stressed enough that the Flemish industrial transition (including its expected higher electricity demand) must ensure access to affordable, secure electricity. Immense deployment of offshore wind in northwestern Europe seems essential for the industrial transition to climate neutrality. Here industrial symbiosis can drive an energy and industrial revolution given that the deployment of offshore will require large amounts of steel, non-ferrous metals and chemical products, giving a boost to regional manufacturing hubs especially these located close to maritime environments. Similarly, the storage of CO2 will require cooperation with countries that have access to storage sites located below the seabed. Hence, in Flanders infrastructure and logistics will need to be developed to access a variety of storage sites. This will require investments in dedicated shipping infrastructure and temporary liquified CO_2 storage.

Possible transition pathway for Flemish industry

Strategically it important to use the strengths of the Flemish industrial ecosystem as a starting point. This includes:

- Location: a key strength of industry (in particular industry located in major clusters) if of course location with easy access to a range of energy sources, raw materials and access to logistics (e.g. shipping). This includes the ability of (publicly owned) port authorities to coordinate and help with execution of (infrastructure) projects.
- value chains and industrial symbiosis: the presence of down- and upstream value chains and industrial symbiosis where companies exchange materials/energy/waste streams
- Networks: the presence of dense and large networks of natural gas, hydrogen and petrochemicals
- Efficiency and process optimisation: a rich history and local know how with regard to process optimisation which contributed to keep industry globally competitive

These factors should be used optimally when planning and developing transition pathways for the Flemish energy intensive industry.

Strengths	*Weaknesses*
• *Central geographical location* • *Excellent connectivity (logistics)* • *At the core of European value (& supply) chains* • *Clustering of production plants/processes and process optimisation (esp. Chemicals & Refining)* • *Strong presence of large multinationals creates positive spill-overs for smaller (local) companies in industrial clusters* • *Refining has due to Integration of world-class stream cracking installations and availability of surplus coking a 'Must Run' status* • *Highly skilled labour force* • *Strong reputation for research and business expenditure on R&D (BERD)*	• *High energy cost related to EU policy (exposure to prices)* • *Most (large) investment decisions are taken by multinational companies with decision making centres outside of Flanders.* • *Relatively high labour costs* • *Regulatory complexity especially for multinationals* • *Open economy and location → vulnerable to international trade disruptions* • *Need for more and updated infrastructure given status as a major logistics hub*
Threats	*Opportunities*
• *Global sectoral developments (US shale gas & shale oil, new investments in Middle East, overproduction in emerging economies like China)* • *EU & global trade disruptive events (e.g. Brexit, US mercantilism, COVID19)* • *Disruptions during the transport and power sector low-carbon transition. The first might weaken the position of refined oil production and hence the link with petrochemicals* • *Industrial low-carbon technologies deployment → (significantly) higher electricity demand → demand for investments in low-carbon power production* • *Circularity → lowered demand of basic products/materials* • *EU ETS → (future) higher CO_2 prices → more carbon exposure → uneven global playing field*	• *Energy/power-sector transition → industrial demand response/storage opportunities* • *Well placed industrial clusters offer opportunities for industrial symbiosis and better economic resilience in a low-carbon economy* • *Circularity → new business models and higher value-added products and services* • *Instrumentalise Know-how and public supported R&D (e.g. moonshots) via demonstration of low-CO2 technologies in Flanders* • *Create lead markets for low-CO2 products and technologies in Flanders via a mission oriented industrial policy*

SWOT Analysis of Flemish Industry in the context of transition to a climate-neutral economy

The main recommendation on the short term is to prepare for large industrial technological demonstration and infrastructure projects that are deemed essential for transition of industry and can be eligible for significant EU funding that becomes available now.

Based on the technology options assessed before, the preparation for the development of carbon capture and transport infrastructure in Port of Antwerp can be seen as a priority activity on short term. CC(U)S will be part of the technology portfolio solutions because:

- Some processes are almost capture ready.
- A mix of technology solutions is in general recommended as to not become highly dependent on a single energy or feedstock vector.
- The infrastructure is forward compatible with future CO_2 utilisation and shorter-term storage of CO_2

Other projects with high relevance are:

- Explore use of integrated steam networks in industrial clusters given that this can replace smaller boilers where carbon capture would be more costly
- Reverse logistics and processes for chemical plastic recycling given that these are mature or close to commercialisation and would fit well inside the Flemish chemicals value chain (with its high focus on polymers)
- Demonstration of blue and green H2 production
- Reinforced connections to renewable electricity production
- Detailed mapping of energy and secondary raw material flows inside and between sectors to explore supra-sector GHG mitigation and efficiency gains to explore full gains of industrial symbiosis (incl. link with e.g. waste, buildings and agriculture).
- Early focus on the challenge of reducing emissions in companies outside industrial cluster (where emissions are mostly due to fossil fuel combustion for generation of heat/steam).

A tentative pathway towards climate neutrality by 2050 would consist of three phases. The period 2020-2030 will be explorative but includes choices that are forward compatible with most future pathways. Important is the development of CO_2 infrastructure (as argued above) but also the demonstration of possible essential technologies for achieving climate neutrality, the first steps in industrial symbiosis between steel and other sectors and chemical recycling. Furthermore, technologies that are not viable at the moment can be explored given their possible large potential in next decades when these might become less expensive due to innovation, learning curves or evolution of prices of feedstock energy. The period 2030-2040 will need the gradual deployment of climate friendly technologies. The deployment choices and rate will depend on state of technology (TRL) on relative cost of feedstock and energy carriers and development of supply chains and networks. The period 2040-2050 will have to see the completion of the transition to climate neutrality by further deployment of most economically and technically appropriate technologies together with reinforcement of supply chains of low-CO2 feedstock, electricity, biomass and waste.

The pathways and roadmap towards 2050 are developed in detail in the other deliverables of this project.

International dimension

Comparing energy intensive industries with neighbouring countries

Germany has the highest energy intensive industries' (EII) emissions followed by France, the UK and The Netherlands. However, The Netherlands has the highest EII emissions as a percentage of economy-wide emissions (after Flanders).

The highest EII emissions reductions between 2008-2018 have come from the UK followed by France. Germany and The Netherlands saw relatively small decreases. The sectors with the highest emissions reductions has been the basic metals sector (UK), paper and paper products (UK), coke and refined petroleum (FR), chemical and chemical products (UK). In The Netherlands, emissions even grew in the food, beverages and tobacco products sector, the chemicals and chemical products sector, and the basic metals sector – the only country in the group to register a growth is emissions amongst the sectors presented above.

The significant decline in the UK and, to a lesser extent, France's EII emissions is related to major industrial closures that ensued over that period. Three large-scale UK refineries (Teesside (Petroplus), Coryton (Petroplus) and Milford Haven (Murco) closed in 2009, 2012, and 2014 respectively. There has also been a reduction of capacity through mothballing of primary distillation[13] while others have registered large losses which led to lower production.[14] Large integrated iron and steel plants in the UK closed in 2010 and 2015 (which included the second largest blast furnace in Europe) in addition to two of three aluminium smelters[15]. In France, there was a large industrial closure in steel production in 2011 (Florange). In Germany, a significant reduction took place in the chemical sector's non-CO_2 emissions, likely similar (catalytic) reduction measures that were taken a bit earlier in Flanders.

Flanders did not see industrial closures of large, single source emitters in the period 2008-2016. While there were important industrial closures in textiles, ceramics and automotive in that period in Flanders, these had a relatively limited impact on overall industrial GHG emissions. Out of all countries assessed here, the industrial emission profile of Flanders is most similar to the one presented for The Netherlands. This does not imply that the overall industrial profile itself is fully comparable between Flanders and The Netherlands.

EII GVA as a percentage of the economy is highest in Germany, followed by The Netherlands, the UK and France. EII GVA as a percentage of economy declined across all countries, however, the biggest loss between the period 2008-2016 was suffered by France (-6%), followed by Germany (-4%). In comparison, The Netherlands (-1%), and UK (-2%) suffered minor reductions. GVA as percent of economy fell most in the basic metals sector across all countries followed by the textiles wearing apparel, leather and related products sector (with the exception of the UK). In the coke and refined products sector, GVA as a percentage of economy fell sharply in the UK and The Netherlands but grew exponentially in

[13] UK Department for Business, Energy & Industrial Strategy, 2017
[14] Critchlow, 2015
[15] Griffin et al., 2016

Germany and France. However, there has been growth in GVA as a percentage of economy amongst all countries in the chemicals and chemical products sector with the exception of The Netherlands at 5 % decline.

Industry is a large employer in all countries compared. German industry direct employment as a percentage of total economy-wide employment is the highest followed by France, the UK and the Netherlands. Between, 2008-2018, the only sector to see positive growth in employment has been the food, beverages and tobacco products sector (2017 for DE, FR; 2018 for UK, NL). Overall, all countries registered large losses between 2008-2016 in EII employment as a percentage of economy-wide employment.

Policy responses in neighbouring countries

Over the past few years the EU and the four neighbouring countries of Flanders have launched a significant number of initiatives that attempt to facilitate industrial transition towards climate neutrality. First, national climate laws have since the Paris Climate Agreement emerged as new governance tools to help manage the low-carbon transition towards net-zero emissions.16 All four of Flanders key neighbouring countries assessed in this report have adopted climate laws with long-term climate-neutrality targets. With the exception of France, the UK, The Netherlands, Germany and even the EU have developed industrial strategies in recent years. There also exist in all four neighbouring countries dedicated hydrogen strategies/initiatives/plans. Additionally, there are plans for infrastructure development and support for low-carbon technologies. Below, these key policy responses to the climate and industrial transition are enumerated and briefly assessed.

Industrial clusters connected to Flanders

Industrial clusters are a concentration of industries in a particular geographical area. To achieve climate neutrality, targeting large industrial clusters offers the most potential. Sizeable industrial clusters allow the deployment of new infrastructure and investments in new innovative processes to take advantage of possible economies of scale like CCS, CO2 transport, H2 production and transport. At the same time, as deeply integrated industrial clusters can also inhibit deep emission reductions17, such strategic planning of infrastructure could lower transition risks and coordination costs compared to a scenario where individual companies and installations would need to plan their climate transitions individually. The largest industrial cluster in Europe lies in the North West of the continent and includes five countries: France, Belgium, The Netherlands, Germany and the UK.

While a comparison with industrial developments in neighbouring countries can give insights into the relative performance of industry in Flanders, it is also relevant to consider how some of the industrial clusters in neighbouring countries are linked to those in Flanders and each other. In particular the chemical and refining industry form part of a broader Northwest European cluster. In the Netherlands, three major industrial clusters are closely related to Flanders: the

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[16] Ecologique, 2020
[17] Janipour et al, 2020

chemical cluster in Terneuzen/Zeeland, the chemical cluster around Maastricht/Geleen and the large industrial activities surrounding the port of Rotterdam. There are ethylene and propylene pipelines connecting Rotterdam, Antwerp and Terneuzen. An ethylene pipeline connection also exists between Antwerp and Geleen. In Germany, there is a large variety of industrial activity in Northrhein Westfalen (Ruhr), and connected by (ethylene) pipeline to Antwerp and next down to other industrial areas in Germany around Frankfurt and Ludwigshafen. In Belgium, there exists an ethylene/propylene pipeline connection from Antwerp to chemicals production in and around Feluy. In Northwest France, there's large industrial activity in Dunkirk (steel, pharma/chemicals) and around Lille.

Analysis of industrial roadmaps and studies

In general, the roadmaps considered in this study show that across a range of industries (steel, chemicals, refining and paper) but also across multiple industrial sectors in a country (Netherlands) or region (Port of Rotterdam) in theory deep emission reductions are possible but challenging. Only in recent years, the case is being made of the possibility of mitigation of up to 100% compared to different historical baselines. In most cases, the deep emission reductions depend on breakthrough technologies that still need to be proven commercially (e.g. CC(U)S and H2 based feedstock/synthetic fuels). In all cases deeper mitigation will require high levels of CAPEX (e.g. EUR 55 Bn for McKinsey & Co 20014 scenario to reduce emissions in Dutch industry by 80% in 2040).

Often the OPEX of the new technologies is higher compared to those currently used. It is also clear that a mix of different technologies will have to applied within and across industrial sectors. The specific mix of technologies will likely depend on local circumstances (e.g. the availability of pure CO2 streams and storage locations, affordable and reliable biomass and/or H2 (via renewable electricity), waste streams from one sector as input for another production process, etc.). It is highly likely, when looking at the roadmaps and the modelled technologies that electricity demand will rise significantly in most decarbonisation scenarios bringing extra challenges to the energy system.

For Flanders, this implies that all the technological options and scenarios presented in the roadmaps will have to be applied and calibrated to the specific regional context (e.g. availability of affordable biomass and H_2, electricity demand). The roadmaps and studies considered in this report are useful in the sense that they look at the bigger picture and international context important for competitiveness. They offer interesting but limited insights into the specific decarbonisation options for Flanders.

Flemish policy initiatives

In Flanders, strategies, policies and instruments which guide the industry climate transition are well in place.

The most prominent of these are:

- The Flemish energy vision (Vlaamse energievisie)
- The Flemish long-term vision (Vlaamse langetermijnvisie)
- The Flemish Climate Policy Plan 2021-2030

- The Flemish action plan on the circular economy (Vlaanderen circulair)
- Voluntary agreements on industrial energy efficiency (Energiebeleidsovereenkomsten)
- Flemish innovation and investment support
- Financing vehicles (e.g. PMV)

This report also provided an overview of specific instruments linked to the policies and strategies mentioned above.

1. Introduction – scope of this report

Scope and goal

This report builds upon the Wyns et al., 2018 study 'Towards a Flemish industrial transition framework' for the Departement omgeving of the Vlaamse Overheid. It further develops the value chains of the industrial sectors that form the focus of this report, alongwith the technologies that can be needed for the transition to a climate neutral industrial which are also explored in detail. The main scope of this report is the chemicals, refining and steel industry, but other sectors will also be briefly presented together with an overview of mitigation options.

This report seeks to address the following elements:

- A description of Flemish energy intensive industries, in practice the sectors covered by the EU Emissions Trading System (EU ETS). This includees overview of production, production technologies, value chains, greenhouse gas emissions, energy use and socio-economic factors such as contribution to GVA, employment and investments.
- An overview of technologies that can facilitate deep greenhouse gas emissions in chemicals, refining and steel, with brief overview of options for other industrial sectors (covered by yhe EU ETS). For each group of technologies, the possible relevance for Flanders is presented together with possible barriers and/or opportunities.
- An overview of technological challenges based on the findings related to low-CO_2 technologies
- A short overview on possible industrial symbiosis including with sectors outside of the scope of this report
- A brief SWOT analysis on Flemish industry in relation to the transition to climate neutrality that is used to develop a general strategic view on transition pathways for Flemish industry, which will be refined with the output of the model developd and used in the overarching project.
- International comparison with neigbouring countries and overview of existing roadmaps and studies on industrial pathways to climate neutrality
- An overview of relevant policies and measures in Flanders

This information presented in this report is based on the following sources:

- Publicly available data
- A broad literature assessment
- Company visits and interviews
- Informal inputs by experts of Flemish research organisations

Chapter guidance

Chapter 2 gives an overview of the greenhouse gas (GHG) emissions, energy use and some socio-economic data from the energy intensive industries: chemicals (NACE 20), refining and cokes production (NACE 19), basic metals (incl. steel and non-ferrous metals, NACE 24), food (NACE 10-12) and beverages, paper and paper products (NACE 17), non-metallic minerals (incl. ceramics and glass, NACE 23), textiles (NACE 13-15) and products of wood (NACE 16).

Chapters 3-8 look at these sectors in-depth. They first provide a comprehensive overview of these sectors in Flanders, followed by a profiling of their emissions, energy use, socio-economic aspects such as gross value added (GVA), employment and investments.

Chapter 9 provides an assessment of technological options for deep greenhouse gas mitigation in chemicals, steel and refining industries together with an overview of mitigation options for the other industrial sectors. For the main technology groups, possible application in Flanders is discussed together with constraints and opportunities where appropriate. Next, a general strategic assessment is developed on cross-sectoral technology challenges. The chapter further looks into industrial symbiosis and concludes by discussing stepwise pathways to climate neutrality. The assessments are based on a broad literature study together with emissions and energy data available for Flanders or calculated based on available data.

Chapter 10 will draw a comparison of industry in Flanders with that of four key neighbouring European countries - Germany, France, The Netherlands and the UK - along three parameters: GHG emissions, GVA and employment, allowing a direct comparison between Flemish industries and those of the neighbouring countries. The chapter also presents the most prominent policy responses of the four countries. The chapter next assesses in detail a large selection of the most reliable European roadmaps and studies on decarbonization of the industrial sectors. From these, lessons are drawn for sectoral decarbonization in Flanders. Finally, an indepth overview of the neighbouring industrial clusters connected to Flanders is presented. Existing and potential interlinkages between these clusters and a (non-exhaustive) list of examples of cooperative projects are explored along with prospects for cooperation at regional and European levels.

Finally, Chapter 11 provides an overview of the current policy framework in Flanders.

2. Energy intensive industries in Flanders: an overview

2.1 Energy intensive industry in Flanders

This chapter provides an overview of the greenhouse gas (GHG) emissions, energy use and some socio-economic data for a selection of industrial sectors. Given that the focus of this report is on energy intensive industries, the scope of this overview is limited to production of chemicals (NACE 20), refining and cokes production (NACE 19), basic metals (incl. steel and non-ferrous metals, NACE 24), food (NACE 10-12) and beverages, paper and paper products (NACE 17), non-metallic minerals (incl. ceramics and glass, NACE 23), textiles (NACE 13-15) and products of wood (NACE 16).

These sectors represent the overwhelming majority of GHG emissions and final energy use in the Flemish industry.

Flanders (still) has a rich eco-system of basic materials industry, spanning a range of diverse sectors and value chains. In general, basic materials producers such as the sectors covered in this report form the foundation of allmost all materials value chains and their downstream applications in the economy as depicted in Figure 1 below.

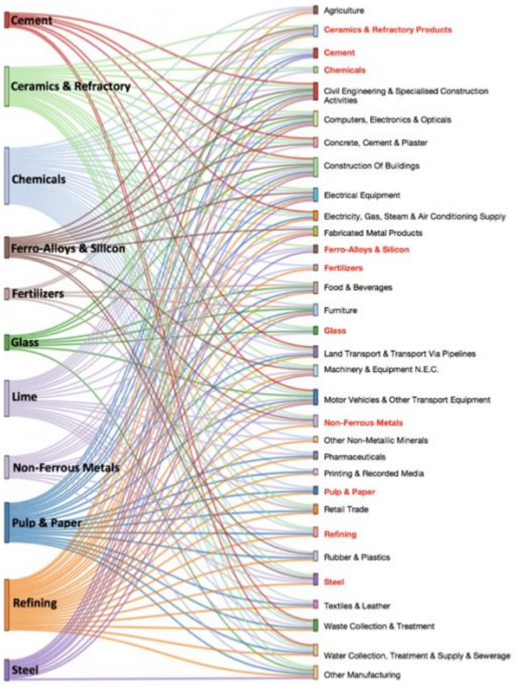


Figure 1: Example of how basic materials producers connect to other parts in the economy, including to each other (red). (Source: Wyns et al., 2018a)

2.2 Greenhouse gas emissions

In 2018, the economy-wide GHG emissions of Flanders stood at 77.7 million tonnes carbon dioxide equivalent (Mt CO_2-eq excl. LULUCF). Since 1990, economy-wide emissions in Flanders decreased 10% (from 86.5 Mt CO_2-eq to 77.7 Mt CO_2-eq).[18]

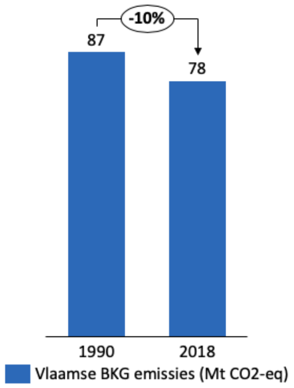


Figure 2: Flemish GHG emissions 1990 and 2018 (Mt CO_2-eq). (Source: VMM, 2020)

Emissions from all industrial sectors (incl. industry not covered by the European Union Emissions Trading Scheme (EU ETS)) stood at 27.9 Mt CO_2-eq (in 2016) or around 36% of total emissions in 2016 a reduction of 13% compared to 1990 (from 32 Mt CO_2-eq in 1990 to 27.9 Mt CO_2-eq in 2016).[19] The energy intensive industries in Flanders, which fall under the scope of the EU ETS, represented 80% (22.4 out of 27.9 Mt CO_2-eq.) of Flemish industrial GHG emissions in 2016. The share of Flemish industrial EU ETS sectors as part of overall Flemish industry fell from 87% to 80% between 2005 and 2016, taking into account the changes to the EU ETS scope in that period[20]. Hence around 20% of industrial emissions fall outside of the scope of the EU ETS in Flanders.

The emissions of Flemish industrial EU ETS sectors fell 16% between 2005 and 2019 (from 26.7 to 22.4 Mt CO_2-eq.), taking into account the changes to the EU ETS scope in that period.

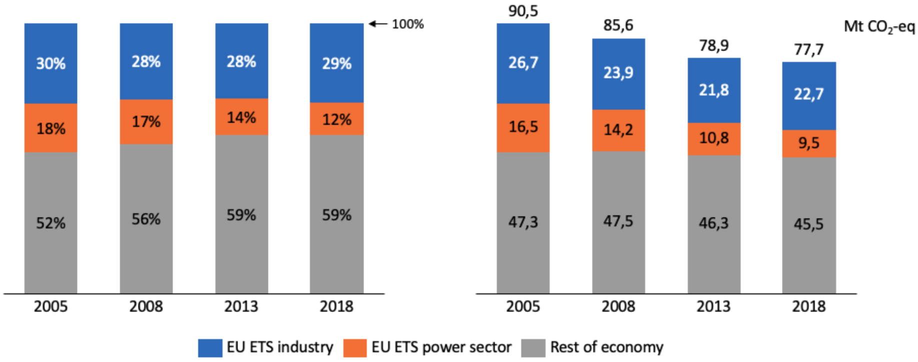


Figure 3: Shares of EU ETS (power and industry) emissions 2005, 2008, 2013 amd 2018 [Left] % and Mt CO_2 eq.[right] (Source: VMM, 2020)

[18] source: VMM, 2020]
[19] This includes both the emissions from industry covered and not covered by the EU Emissions Trading System. Source: luik mitigatie 2017 in Vlaams Overheid 2018
[20] The changes to EU ETS scope are discussed in the Vooruitgangsrapport – luik mitigatie 2017 in Vlaams Overheid 2018 p. 24

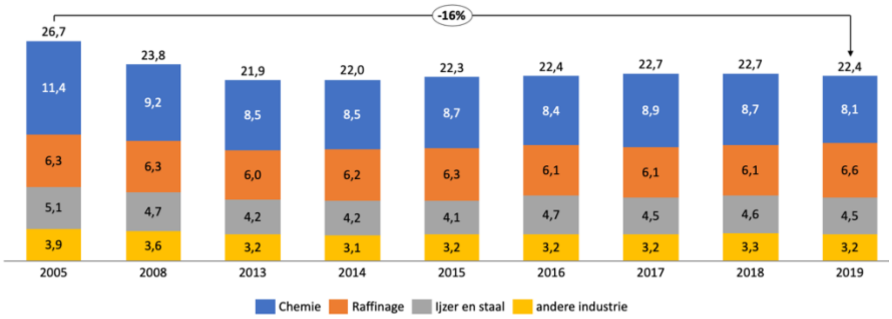


Figure 4: Evolution of GHG emissions under EU ETS (Mt CO_2-eq.). (Source: Vlaamse Overheid, nieuwsbrief emissierechten, 2020)

The most significant emission reductions ensued in the chemicals sector (from 11.4 to 8.1 Mt CO_2-eq - a reduction of 29%) and in the ceramics, non-ferrous, food and textiles industries (as a combination) (from 3.9 to 3.2 Mt CO_2-eq. - a fall of 18%) over the same period.

Part of the emission reductions in the latter sectors can be explained by industrial closures during the period. In particular, smaller industries such as ceramics and textiles, but also the automotive industry, were affected more significantly by those industrial closures. The sensitivity to closures indicates that an intelligent approach towards industrial transformation for Flanders must be designed to avoid risking the erosion of industry competitiveness since closures will negatively impact welfare in Flanders and simply shift emissions to more competitive regions.

There exists a strong concentration of large industrial GHG emitters (under the EU ETS) in Flanders both on a sectoral and site basis (Fig. 5). On a sectoral basis the combined refining, chemicals and iron and steel sectors in Flanders represented almost 86% of Flemish industrial emissions covered by the EU ETS in 2019.

The top 40 of the largest industrial emitters accounted for around 90% of industrial EU ETS emissions. The top 10 largest industrial emitters accounted for around 70% of Flemish industrial EU ETS emissions.

The top 40 list consists of all (large) refineries and steel producers. Most of the remaining large emitters in the list are chemicals producers. The rest include 6 food and beverages companies, 3 paper producers, 2 non-ferrous companies and one company each of ceramics, textile and glass production.

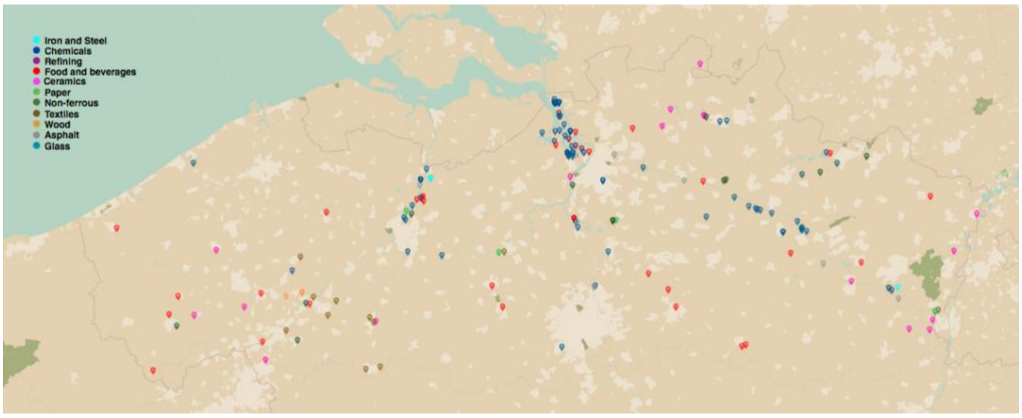
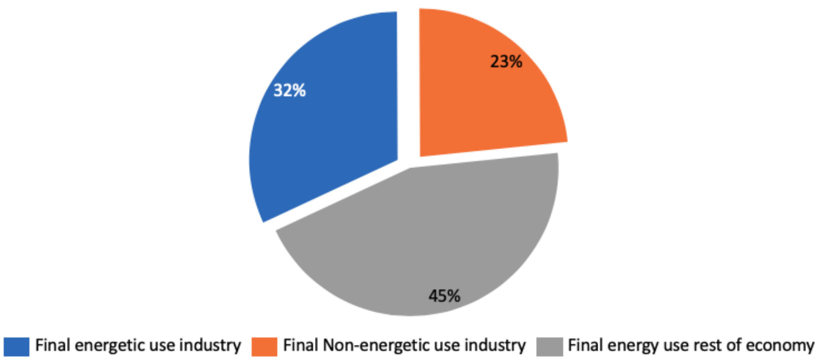


Figure 5: Mapping of industrial EU ETS sites in Flanders. (SourcesWyns et al., 2018b; Vlaamse Overheid, Departement Omgeving , afdeling EKG, 2017)

2.3 Energy use

In 2017, the final[21] Flemish energy use was 1,245 PJ. The final energy use by industry was 396.7 PJ. The non-energetic (feedstock) use was 292 PJ or 23.5% of the Flemish total energy use. The total energy use by industry (both as feedstock and for energetic use) was 688.7 PJ or 55% of final Flemish energy use.



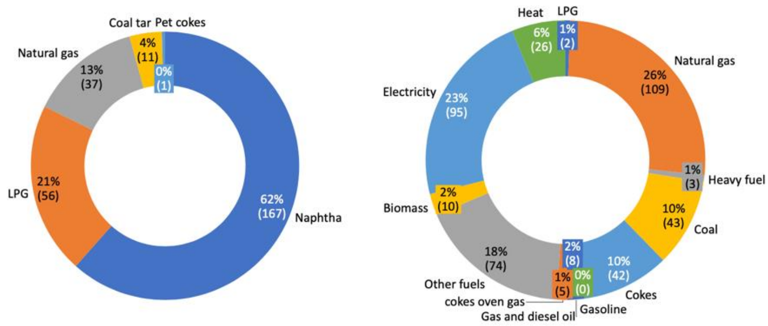


Figure 6: Industrial non-energetic use of fuels (left) and final energy use (right) by industry. % and (absolute-PJ) in 2017. (Source: Vito, 2019)

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[21] Excluding energy use in transformation of energy and bunkers.

The main fuel sources (non-energetic) are naphtha (167.1 PJ), LPG (56.2 PJ) and natural gas (36.5 PJ). The main source for final energetic use are natural gas (109.2 PJ), electricity (94 PJ) and other fuels (most derived from naptha and LPG non-energetic use) coal (42.6) and cokes (41.9 PJ).

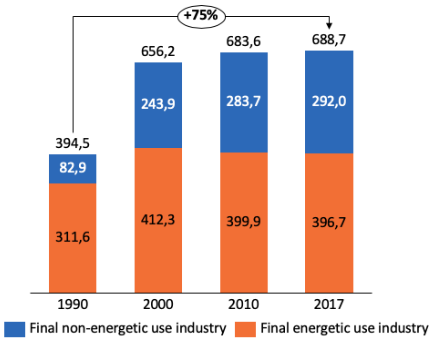

Figure 7: Evolution of final energy use of Flanders in industry (1990, 2000, 2010 and 2017 (PJ) (Source: VITO, 2019)

Compared to 1990, the total final energy use in Flanders went up 47% (from 852 to 1,245 PJ), with industrial energy use (incl. use as feedstock) rising 75% (from 394.5 to 688.7 PJ) - the major contributor to this increase. In industry, the non-energetic final energy use saw the biggest increase from 82.9 PJ in 1990 to 292 PJ in 2017, or an increase of 250%. The total final energy use excluding feedstock in Flanders increased 17% (from 769 to 903 PJ) over the same period, with industrial energy use (excl. use as feedstock) rising 13% (from 312 to 385 PJ). However, most of the increases in energy use happened between 1990 and 2005 with energy use remaining stable after.

2.4 Socio-economic: Value added, employment, investments

The industrial sectors chemicals and chemical products, basic metals, refining and cokes, food/drinks/tobacco, wood, paper, non-metallic minerals and textiles)[22] represented 9.1% of the Flemish GVA in 2017. In 2005, this was 10.7%. The absolute GVA for these sectors increased from EUR 18.6 Bn in 2005 to EUR 21.5 Bn in 2017, an increase of almost 16%.

[22] Represented by NACE 10-12, 13-15, 16, 17, 19, 20, 23 and 24

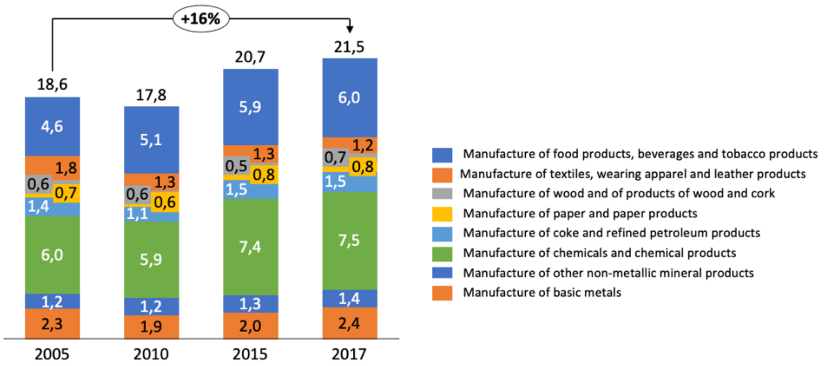

Figure 8 GVA of the industrial sectors (absolute figure in EUR Bn) 2005-2018 (Source: NBB, n.d.)

Over the same period (2005-2018), the total Flemish GVA (current prices) increased by 46% - from EUR 160 Billion (Bn) to EUR 233 Bn. This explains the declining share of these industries contribution to the Flemish economy wide GVA.

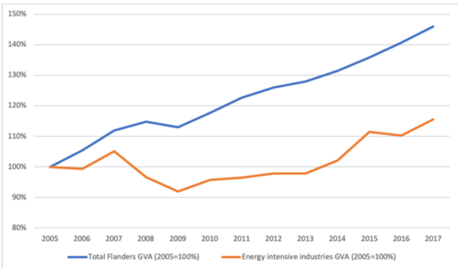

Figure 9: Relative evolution of Flemish economy wide GVA and aggregate of Flemish energy intensive industries. (2005=100%). (Source: NBB, n.d.)

The evolution of the energy intensive industries' GVA shows the impact of the economic crisis as from 2008, with GVA recovering to pre-crisis levels only in 2013-2014.

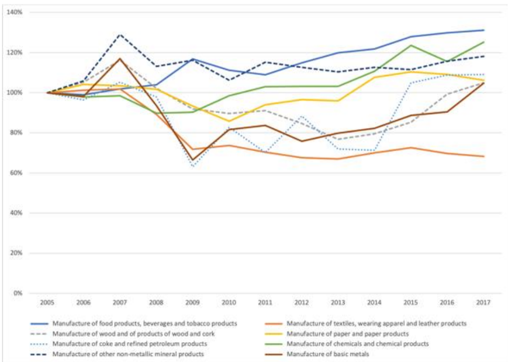

Figure 10: Relative evolution of sectoral GVA (2005=100%). (Source: NBB, n.d.)

Most sectors were impacted by the crisis as from 2008 with exception of the food and beverages industry.

The industrial sectors (as aggregate of industrial NACE codes[23]) registered a 15% decline in employment - from 207,600 to 176,300 persons between 2005 and 2018. Indirect employment is not considered here.

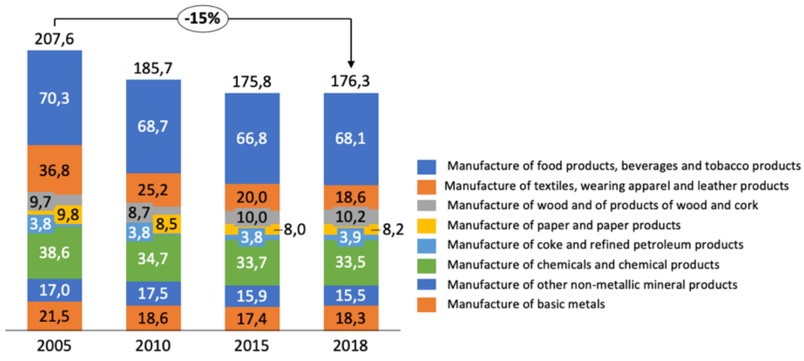

Figure 11: Number of persons employed of the industrial sectors together (absolute figure in 1000s) 2005-2018 (Source: NBB, n.d.)

Also, the share of number of people employed by these industries compared to total Flemish employment fell from 8.5% to 6.2% between 2005 and 2018. In the same period, the total employment (number of persons) in Flanders grew 15% - from 2.45 Million (Mn) persons to 2.82 Mn persons.

Again, there are significant differences between sectors but the downward trend in direct employment was present in almost all industries covered here.[24]

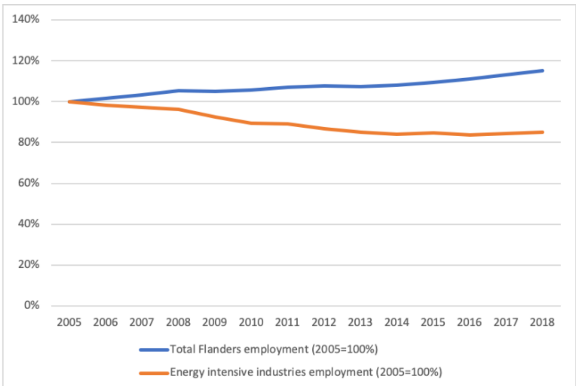

Figure 12: Relative evolution of Flemish employment and aggregate of Flemish energy intensive industries. (2005=100%). (Source: NBB, n.d.)

Between 2005 and 2017, total investments in the industrial sectors covered here[25] have grown steadily from EUR 2.08 Bn to EUR 3.66 Bn. 2017 seemed to be an exceptional year as concerns investments which were EUR 800 Mn higher than the 2016 figures (EUR 2.8 Bn). Between 2005-2016 the share of industrial investments as a percentage of total investments in Flanders hovered between 12-15%. In 2017 this figure was 16%.

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[23] Represented by NACE 10-12, 13-15, 16, 17, 19, 20, 23 and 24
[24] The sectors covered here do also have an important part of subcontracted employment, but specific data was not directly available for an assessment in the context of this study.
[25] Aggregate of NACE 10-12, 13-15, 16, 17, 19, 20, 22, 23 and 24

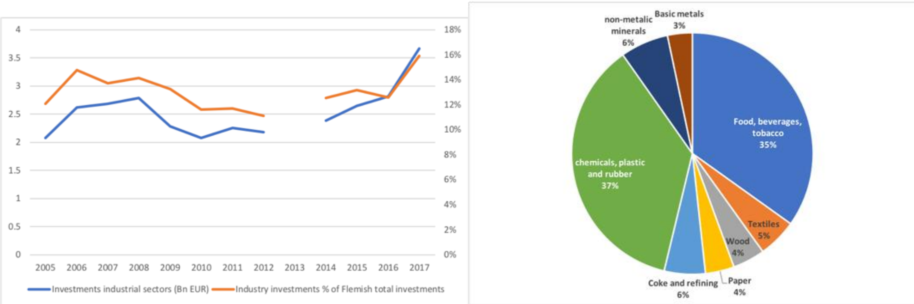

Figure 13: [Left] Energy intensive industry investments in Flanders (in EUR billions and as a percentage between 2005 and 2017 – 2013 data missing), and [Right] Share of investments in Flanders amongst energy intensive industries. (Source: NBB, n.d.)

3. Chemicals industry in Flanders – A Profile

3.1 Overview

The Flemish basic and fine chemicals industry, together with the production of plastics and rubber and pharmaceuticals, forms an important part of the industrial backbone of Flanders. The sector is diverse, with high volume basic chemicals produced by large multinational corperations, but also a large variety of smaller scale specialty chemicals produced by small and medium sized enterprises (SMEs).

The Flemish chemicals industry, together with crude oil refining, can be seen as a large and strongly linked eco-system. The chemical value chain in Flanders is well developed and closely integrated with major product and energy transfers between companies, in particular but not exclusively, those which are located in the Antwerp petrochemical cluster.

Most of the activities of the chemicals industry in Flanders are located in the Port of Antwerp. Other major chemical production activities take place in a wider area around Tessenderlo and linked to the Albert Canal (linked to chlorine and polymers production). Finally, smaller activities related to chemicals (incl. bio-based chemicals) take place in the Ghent-Zeebrugge harbor area.

The petrochemical cluster in Antwerp is considered to be the the largest integrated petrochemical cluster in Europe and the second largest in the world after the Port of Houston, USA. This is reflected by the presence of three world class steam-cracking facilities, propane dehydrogenation as well as other large basic chemicals production plants (e.g. ammonia).

Chemical products are present in all downstream value chains of the economy and are increasinngly essential to achieving climate neutrality (e.g. battery chemistry, materials for wind-turbines and low-weight vehicles).

Specific production data for Flanders was not available, hence Belgian prodcom data was used to chart the main product categories by the chemical industry. Given that the overwhelming majority of chemical sector activies take place in Flanders, this is a good indicator of the sectors' production landscape.

The value of deliveries in 2018 for chemicals produced in Belgium stood at EUR 31 Bn. Most important contributers are basic organic chemicals and polymers (each 32%) but also a very diverse group of mostly fine chemicals (12%). Within the organic chemicals a-cyclic and cyclic hydrocarbons form the biggest component (37% of value in organic chemicals) together with organic chemicals with nitrogen component (11%), organic chemicals with sulphur component (13%) and a group including ethers and peroxides (7.5%).

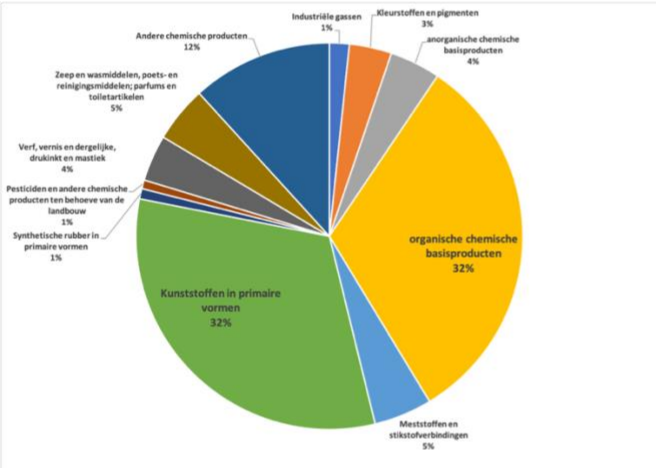

Figure 14: Relative production value of chemical products in Belgium in 2018. (Source: Statbel – Prodcom)

Most polymers are build from basic organic chemicals (sometimes in combination with chlorine, ammonia or other inorganic chemicals) and hence there exists a strong link between organic chemicals (e.g. high value chemicals such as ethylene and propylene) and polymers, which together form the largest bulk of chemicals produced.

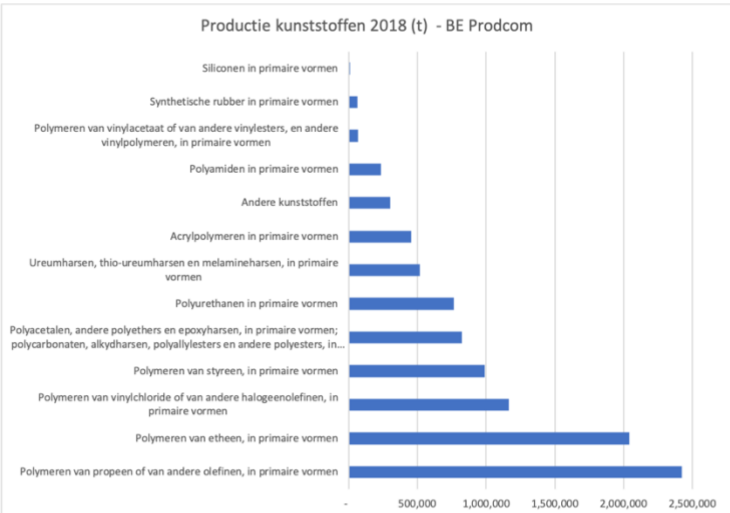

Figure 15: Production volumes of polymers in Belgium in 2018 (t). (Source: Statbel-prodcom)

The total amount of polymers produced in Belgium (large majority of which produced in Flanders) was 9.8 Mt in 2018. Propylene and ethylene form the largest groups of polymers produced. But also, polymers based on vinylchloride (e.g. PVC), styrene and polyurethane are produced at scales of 500 kt to 1,000 kt per year.

The production of basic organic chemicals (and related polymers) together with ammonia production form the the most energy and greenhouse intensive parts of the chemical industry in Flanders. From the perspective of energy and feedstock use and GHG emissions, half of the EU ETS emissions of the chemicals industry (including steam-cracking located at refining) in Flanders can be attributed to important processes at the beginning of important chemical value chains:

1. Steam-cracking → High value chemicals (ethylene, propylene, butadiene, benzene, toluene and xylene)
2. Propane dehydrogenation → propylene
3. Ammonia production (using hydrogen from steam methane reforming)
4. Steam methane reforming for hydrogen (and syngas) production

While much less GHG emissions intensive, chlorine production is another major starting point of the chemical value chains in Flanders. It is used in the production of polyurethane and PVC.

Figure 16 below illustrates the value chains for the production of important polymers in Flanders.

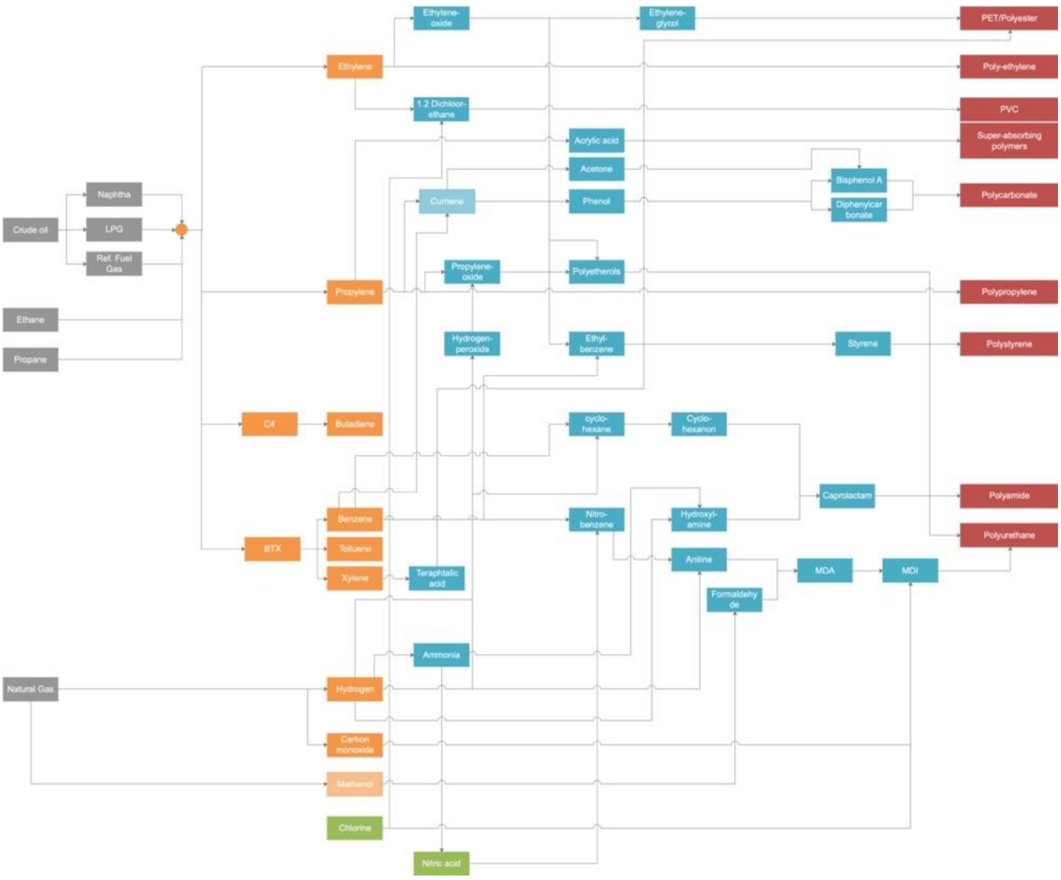

Figure 16: Petrochemical value chain towards major polymers (Sources: extracted from the GBPV/IPCC database Departement Omgeving – Vlaamse Overheid)[26]. Grey: basic material inputs, Orange: high value chemicals, Green: non-organic basic chemicals, Blue: intermediate products, Red: polymers. Light colours: production not or very limited in Flanders.

3.2 Greenhouse gas emissions

The Flemish chemicals industry is, along with steel production and crude oil refining, the largest GHG emitting sector under the industrial sectors covered by the EU ETS and industrial emissions at large in Flanders.

[26] https://omgeving.vlaanderen.be/overzicht-gpbv-installaties-in-vlaanderen-industrie

The chemicals industry represents 36.6% of the industrial GHG emissions under the EU ETS in Flanders in 2019. In 2005 this share stood at 43%.

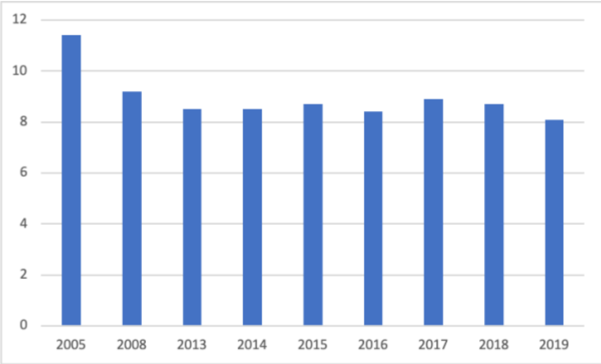

Figure 17: Evolution of GHG emissions chemical industry covered by EU ETS in Flanders (Mt CO_2-eq.) (Source: Vlaamse Overheid, Departement Omgeving , 2019)

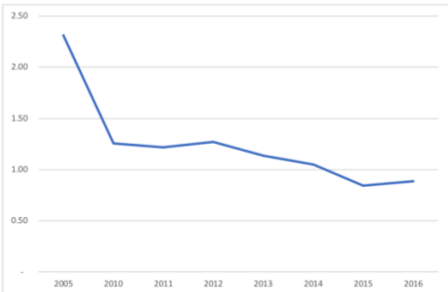

Figure 18: N_2O emissions from chemicals industry in Flanders between 2005 and 2016 (Mt CO_2-eq.) (Source: VMM, 2016)

Between 2005 and 2018, emissions from the chemicals industry dropped 29% (from 11.4 Mt CO_2-eq to 8.1 Mt CO_2-eq). Since 2013 emissions have remained mostly flat. A significant part of the reduction between 2005 and 2018 came about from the mitigation of N2O emissions from chemical production processes.[27]

However, process efficiency improvements have played an important role too especially when taking into account the fact that the GVA of the chemicals industry (basic chemicals and chemical products) increased by 27% between 2005-2018 which shows a decoupling between emissions and production. The emission intensity (measured as CO_2 emissions/GVA) was reduced by 40% between 2005 and 2018.

Because chemical activities are concentrated in Flanders the related emissions are too. Out of the chemicals sector GHG emissions under the EU ETS in Flanders in 2018, 83% occurred in the Port of Antwerp, 9% in the wider zone around the Albert Canal and 3% in the Ghent harbor area (Figure 19). The remaining 5% emisions are taking place at smaller installations accros Flanders.

[27] In particular the N_2O emissions from nitric acid production dropped from 2 Mt CO_2-eq. in 2005 to 0.4 Mt CO_2-eq. in 2013. Source: Vlaamse Overheid, 2018, p. 26

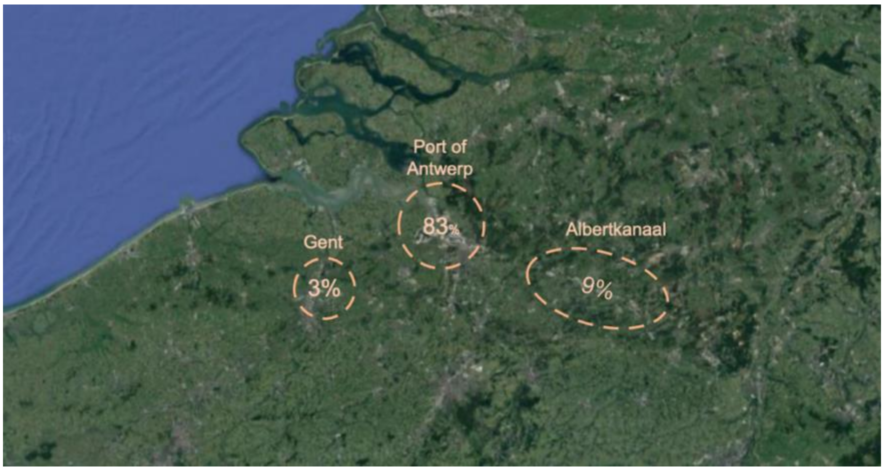

Figure 19: Concentration of chemical sector EU ETS covered GHG emissions (2018)

Not only is the location of emissions concentrated, but also the emissions in processes are concentrated with a small number of industrial process installations responsible for the majority of emissions. Around 50-55% of chemical sector GHG emissions are related to naphtha cracking, steam methane reforming, ammonia production and propane dehydrogenation. These represent 7 process installations. The remaining emissions include N_2O from caprolactam production and mostly emissions related to boilers and turbines for steam production.

3.3 Energy use

Energy consumption (use of fuels as feedstock and energetic use) of the Flemish chemicals industry increased between 1990 and 2017 (from 164 PJ to 422 PJ), with a major leap between 1990 and 1994.

Currently, the chemicals industry is responsible for 33% of the final energy use in Flanders and 61% of Flemish industrial final energy use for both feedstock and energetic use (Figure 20).

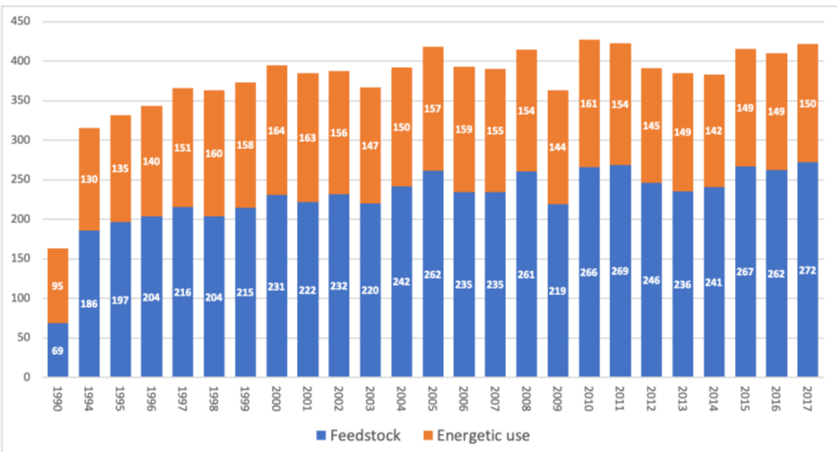

Figure 20: Evolution of feedstock and energetic use of fuels in Flemish chemicals industry between 1990 and 2017 (PJ) (Source: VITO, 2019)

Naphtha together with Liquefied Petroleum Gas (LPG) are the main feedstocks for steam-cracking installations in the Flemish petrochemicals industry (e.g. for ethylene, propylene, butadiene, and aromatics production) (total 220 PJ in 2017).

New installations and expansions in the 1990s led to an increase in demand. Since naphtha is an important distillate in crude oil refining, there exists close integration between some of the basic chemicals production in Flanders with the refining industry. This link has strengthened over time. In 1995, the refining output covered only 20% of the chemicals sector's naphtha demand. In 2017, this share increased to almost 70% (see Figure 21). Recently a shift towards lighter feedstock is ensuing with higher levels of LPG and ethane being used in steam-cracking in Flanders.

Natural gas also forms an important feedstock in the chemicals industry, in this case for ammonia, hydrogen and syngas production.

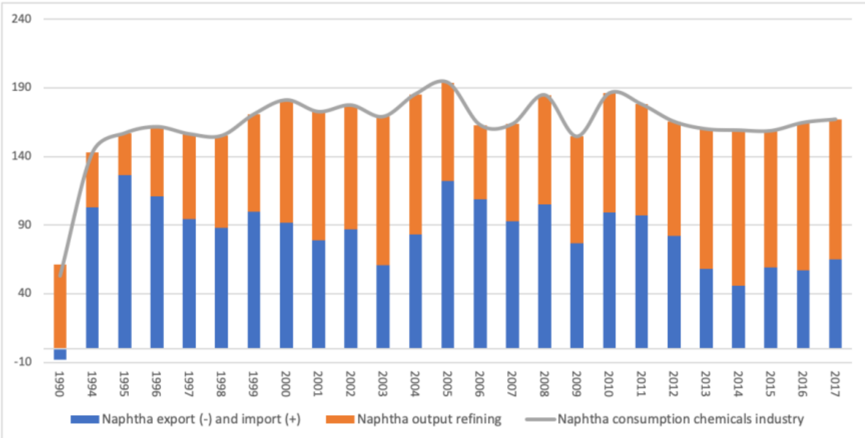

Figure 21: Evolution of Naphtha imports, production in Flanders and consumption by the chemicals industry between 1990 and 2017 (PJ) (Source: VITO, 2019)

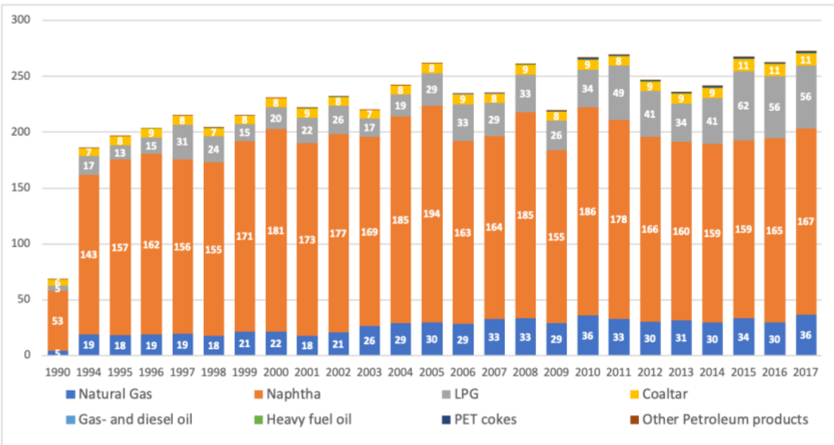

Figure 22: Evolution of feedstock use of fuels by Flemish chemicals industry between 1990 and 2017 (PJ) (Source: VITO, 2019)

With regard to the energetic use, the most important source for the chemicals industry is fuel derived from naphtha cracking processes (defined as other fuels in table below – 72 PJ in 2017). This fuel is mostly autoconsumed in the steamcracking or propane dehydrogenation installations.[28] Hence the total energetic and non-energetic use in these installations is 292 PJ (2017) or around 70% of the total energetic and non-energetic use of the chemicals industry. Add to this the non-energetic (feedstock) use of natural gas for hydrogen, ammonia and syngas (36 PJ in 2017) and the total use of fuels for steamcracking, propane dehydrogenation, ammonia and steam methane reforming is 328 PJ or 78% of the total energy use in the chemicals industry.

The remainder energy use of the chemicals industry is met by natural gas and electricity. The electricity use by the chemcials sector in 2017 was around 10 TWh (37 PJ) this represents around 12% of Belgian power consumption. It must be noted that the chemical industry also produces electricity via cogeneration.

After the significant rise in energy use in the 1990s, there has been a stable trend until 2017, although production continued to increase (Figure 23).

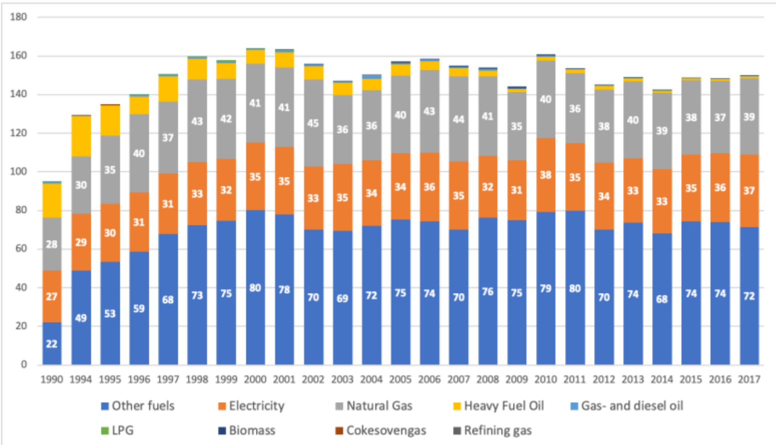

Figure 23: Evolution of energetic use of fuels by Flemish chemicals industry between 1990 and 2017 (PJ) (Source: VITO, 2019)

3.4 Socio-economic: Value added, employment, investments

In the period 2005 to 2018, the GVA of chemicals production (NACE 20) in Flanders increased by 27% (from EUR 6 Bn to EUR 7.6 Bn). On the other hand, the share of the chemicals sector contribution to the Flemish GVA decreased from 3.8% to 3.2% over same period.

Employment in chemicals production fell 13% between 2005 and 2018 (from 38,616 persons to 33,450 persons). The share of employment to the total Flemish economy dropped from 1.6% to 1.2% in the same period.

The chemicals industry (including plastics and rubber) is the largest industrial investor in Flanders. During 2005-2017,[29] the sector invested EUR 11.1 Bn,

[28] VITO, 2019
[29] Minus the year 2013 for which no data was available.

which represented 4.8% of the total investments in Flanders over that period.

4. Refining industry in Flanders – A Profile

4.1 Overview

Flanders has three large crude oil refineries (operated by Exxonmobil, Total and Gunvor). The Flemish refining industry forms part of the petrochemical cluster in the Port of Antwerp and is closely integrated with the chemicals industry. One refinery is integrated with petrochemicals production with the presence of two world class steam-cracking installations.

The main input material for refining is crude oil. In 1990, the input of crude oil in Flemish refineries stood at 1,250 PJ, growing to almost 1,940 PJ in 2002, and declining afterwards. In 2017, the energy input stood at 1,501 PJ (or around 245 Mn barrels of oil equivalent).

The main refining outputs (measured in PJ) in 2017 were gas- and diesel-oil (37%), heavy fuel oil (20%), gasoline (14%), other petroleum products (11%), naphtha (7%) and kerosene (6%). Between 1990-2016 there was a slight increase in the shares of gas- and diesel-oil (from 35% to 37%) and naphtha (from 5% to 7%) while the share of gasoline decreased (from 19% to 14%) (Figure 24).

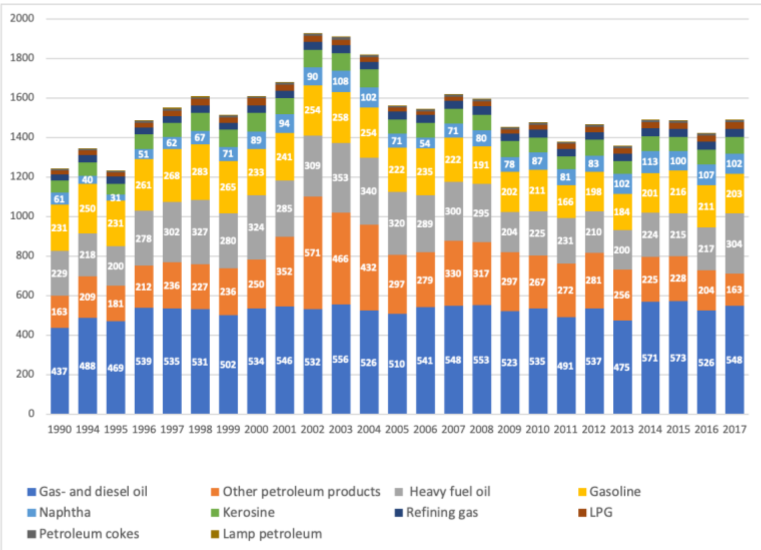

Figure 24: Outputs of crude oil refining in Flanders 1990 to 2017 (PJ) (Source: VITO, 2019)

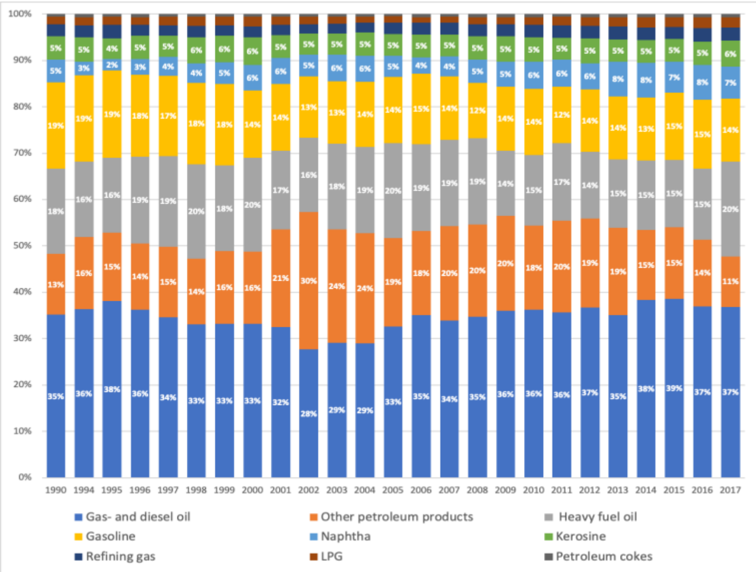

Figure 25: Relative outputs of crude oil refining in Flanders 1990 to 2017 (Source: VITO, 2019)

The outputs from the refining process serve most of the rest of the economy. Naphtha and LPG form key feedstocks for chemical processes. Gas- and diesel oil is used as fuel in the chemicals industry, many other industrial sectors, in the residential sector (heating), and foremost in the road transport sector. Gasoline is also used for road transport, while kerosine sees its use in aviation. Heavier fuels are used in (international) shipping. Heavy refining residues such as bitumen find applications in roadworks (e.g. asphalting).

Out of the 537 PJ petroleum products used for final consumption in Flanders (2017), around 260 PJ (48%) is used in industry (with 245 PJ as feedstock/non-energetic use). 67 PJ (12%) of petroleum products are used in the residential sector and 211 PJ (39%) in transport.[30]

4.2 Emissions and energy use

The GHG emissions from crude oil refining (with scope as reported under the EU ETS) in Flanders increased by 19% between 2005-2019 with emissions in 2005 standing at 5.6 Mt CO_2-eq and at 6.6 Mt CO_2-eq in 2019. The share of crude oil refining emissions as part of the Flemish industrial EU ETS emissions is around 30%.

Within refineries in Flanders, the majority of emission resides in the furnaces, boilers, fluid catalytic cracking and regeneration of catalysts, cogeneration and (separate) hydrogen production for desulphuring. But also, where present, in the production of basic chemicals via steamcracking.

[30] Vito, 2019

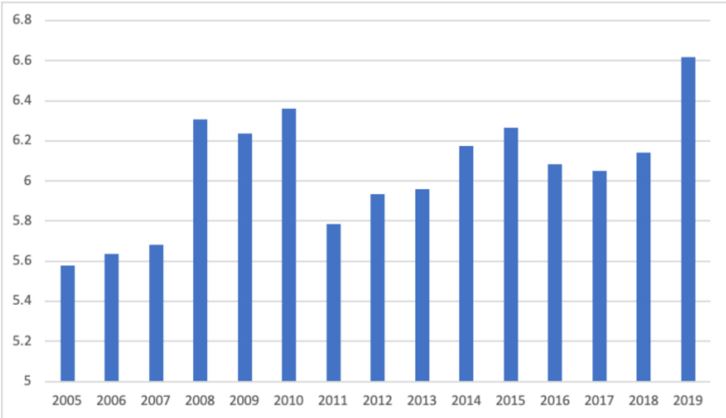

Figure 26: Evolution of GHG emissions of the refining industry covered by EU ETS in Flanders (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

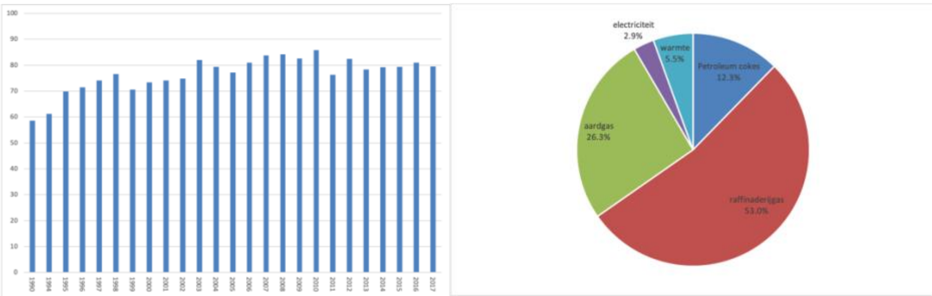

Figure 27: [left] autoconsumption of energy in refining, [right] autoconsumption per fuel (2017) (Source: VITO, 2019)

Between 1990 and 2017, the energy use in the refining sector (i.e. autoconsumption) went up by 36% with large increase between 1990-2004, after which the energy use went down a little and stabilised around 80 PJ/a. The majority of energy in refining is refining gas which is generated during the refining (distillation) processes. The use of natural gas has increased from 2.6 PJ in 2000 to 20.8 PJ in 2017. Refining is next to the steam methane reformers in the chemicals industry the largest producer of hydrogen in Flanders. In the Flemish refining industry major initiatives have been taken to recover valuable gases and fuels from refinery off-gasses.

When looking at the energy use per unit of output, there has been an increase over the period 1990-2017. This is likely due to stricter regulation on sulphur in fuels and hence higher energy consumption. Between 2002-2004 the specific energy use was notably lower, but this is likely related to the high output in this period showing a full/optimal use of refining capacity.

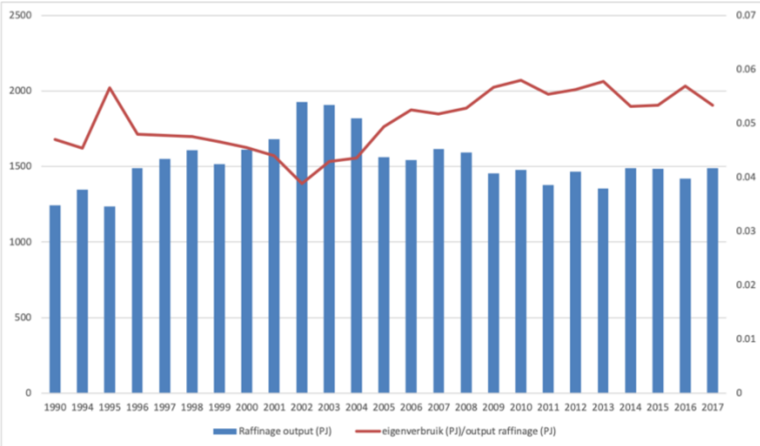

Figure 28: The refining total output (PJ) and the energy use in refining per unit of output (Source: VITO, 2019)

4.3 Socio-economic: Value added, employment, investments

Between 2005 and 2017, the GVA of refining of petroleum products and cokes production in Flanders increased 9% (from EUR 1.4 Bn to EUR 1.5 Bn). On the other hand, the share of this sector's contribution to the Flemish GVA decreased from 0.9% to 0.65% over same period.

Employment increased 2% between 2005 and 2018 (from 3,843 persons to 3,918 persons): the only one out of all industrial sectors listed here to see an increase. Employment share of petroleum products and cokes production to total employment in the Flemish economy dropped slightly from 0.16% to 0.14% in the same period.

During 2005-2017[31], the refining (and cokes) industry invested EUR 1.7 Bn, or 0.7% of the total investments in Flanders during that period.

[31] Minus the year 2013 for which no data was available.

5. Steel industry in Flanders: A profile

5.1 Overview

There are two major steel producers in Flanders. In Ghent, there is an integrated steel-plant owned and operated by ArcelorMittal. In Genk, smaller amount of steel is produced by Aperam via electric arc furnaces (EAF) using scrap steel as input material.

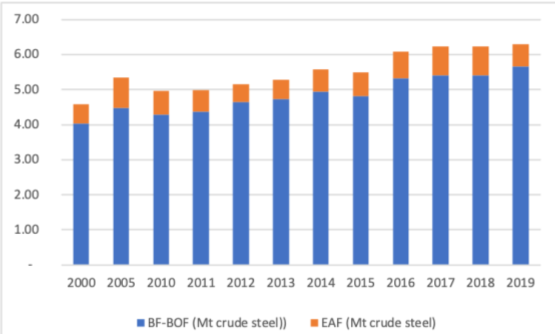

Figure 29: Steel production in Flanders (Source: Steelbel, n.d.)

In 2019, total crude steel production in Flanders stood at 6.29 Mt. Between 2000 and 2019 total production increased by 37%. In 2019 90% of crude steel produced in Flanders ensued via the BF-BOF route and 10% via EAF.

Steel is used in almost all other (manufacturing) sectors of the economy. The integrated steel BF-BOF production in Flanders has major consumers in the automotive industry (including the use of high-strength steel), transport, construction, machinery, household appliances, wind-turbines, construction and building sector, and packaging. Stainless steel production via EAF in Flanders finds applications in the energy industry, household appliances, catering, building and construction, automotive, industrial applications and aeronautics.

5.2 Emissions

The GHG emissions of steel production in Flanders (as defined by the EU ETS) were 4.4 Mt CO_2-eq in 2019 or 20% of the Flemish industrial GHG emissions covered by the EU ETS. Since 2005 (5.1 Mt CO_2-eq), these emissions reduced 9%. This does exclude the emissions from combustion of siderurgical gases (from steel production) used in power generation which were 5.2 Mt CO_2-eq in 2019. Since 2005 these emissions have increased almost 44%.

The total emissions from BF-BOF steel increased 12% between 2005-2019 (from 8.5 Mt CO_2-eq to 9.5 Mt CO_2-eq). The (direct) emissions from EAF steel decreased by 25% over same period (from 0.186 Mt CO_2-eq to 0.140 Mt CO_2-eq). 99% of Flemish steel sector emissions occur via the BF-BOF route.

Given that total steel production went up 18% between 2005 and 2019, the GHG intensity of steel production reduced in Flanders.

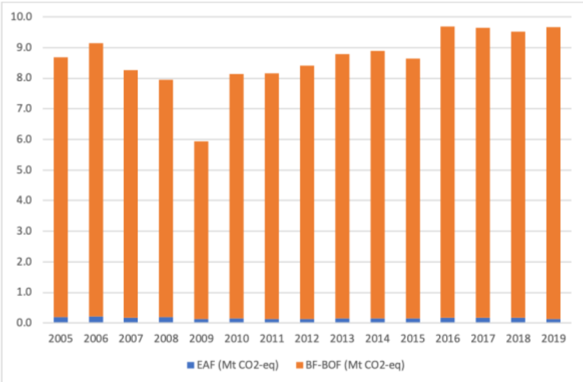

Figure 30: Evolution of GHG emissions by Flemish steel production under EU ETS and emissions from use of siderurgical gases in power generation (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2019).

5.3 Energy

In 2017, the final energy use of the steel industry was 83.5 PJ or 7% of total final energy use in Flanders and 12% of Flemish industrial final energy use. The final energy use in steel production in Flanders remained relatively stable between 1990-2017 (Figure 31). Most of the energy inputs for steel production in Flanders come from cokes and coal. In the period 1990-2017, the amount of blast furnace gas produced steadily increased, most of which was used for electricity production.[32]

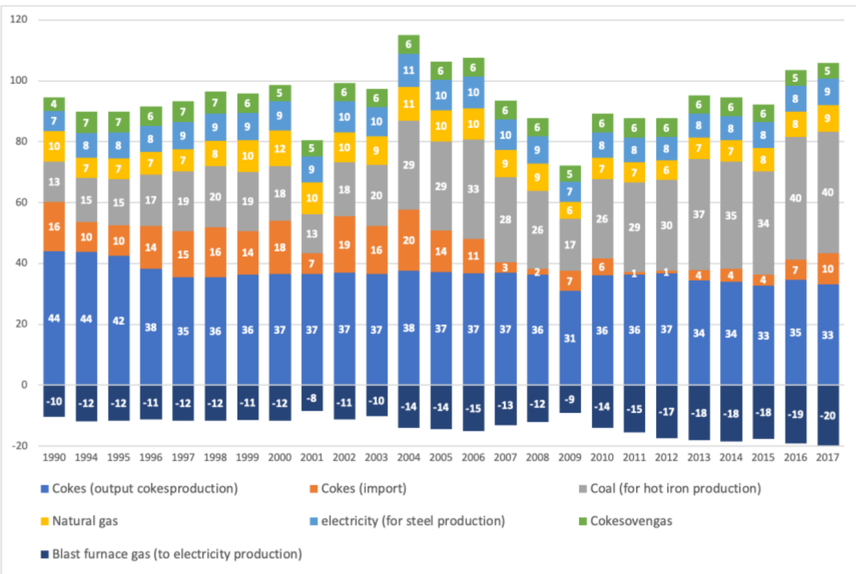

Figure 31: Evolution of energy use in steel production (excl. transformation of coal to cokes) in period 1990-2016 (PJ) (Source: VITO, 2019)

[32] VITO, 2019

5.4 Socio-economic: Value added, employment, investments

The socio-economic data uses the NACE 24 classification which includes next to steel production also other non-ferrous metals production.

Gross Value Added

In the period 2005-2017, the GVA of the manufacturing of basic metals in Flanders increased 5% (from EUR 2.3 Bn to EUR 2.4 Bn). The share of these sectors' contribution to the Flemish GVA decreased from 1.43% to 1.03% over the same period.[33]

Employment

Employment in manufacturing of basic metals in Flanders fell 15% between 2005 and 2018 (from 21,479 persons to 18,334 persons). Employment as a share of the total employment in the Flemish economy dropped from 0.88% to 0.65% in the same period.[34]

Investments

The basic metals industry invested EUR 1 Bn between 2005 and 2017[35], or 0.4% of the total investments in Flanders during the same period.

[33] Source: NBB, n.d., Regionale rekeningen, A38, NUTS 2
[34] ibid.,
[35] Minus the year 2013 for which no data was available.

6. Paper and cardboard industry in Flanders: A profile

6.1 Overview

In Flanders, four companies in the sector paper and cardboard production are includeed in the EU ETS. The total production capacity is around 1.5 Mt per year. These companies serve different value chains:

- Coated paper (heat-set web offset print) – 490 kt/pa capacity
- Cardboard (from recycled paper and cardboard) - approx. 500 kt/pa capacity
- Recycled newsprint and magazine paper – 540 kt/pa capacity
- Hiegenic and household paper products – approx 40 kt/pa

The main input materials for paper and cardboard production are recycled paper and cardboard, purchased pulp and wood (for pulping). More than half of Flemish paper and cardboard production uses recycled materials as input. The paper industry is a major user of biomass in Flanders.

Most plants are located outside of large industrial clusters.

6.2 Emissions

Paper and cardboard production are responsible for a small share of industrial GHG emissions in Flanders, with emissions standing at 0.54 Mt CO_2-eq in 2019 or 2.4% of industrial emissions covered by the EU ETS in Flanders. Between 2005 and 2019, the emissions of paper and cardboard production increased by 15% (Figure 32).

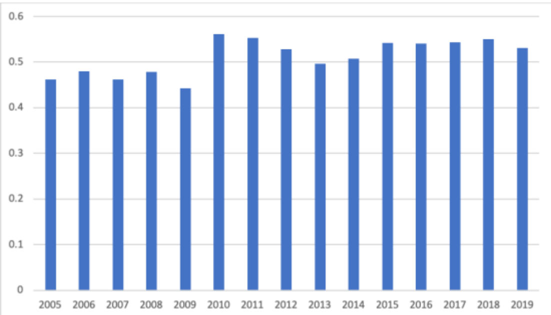

Figure 32: Evolution of GHG emissions of paper industry under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

6.3 Energy

The final energy use of the paper industry (including publishing) increased 36.5% between 1990 and 2017 (from almost 12PJ to 16PJ), with a significant jump in consumption between 2009-2010 (see Figure 33). Important to note is the significant increase in the use of biomass from zero to 5.7 PJ in 2017, representing 35% of the final energy use in paper and cardboard production in Flanders and 55% of the total biomass energy use in industry in Flanders.

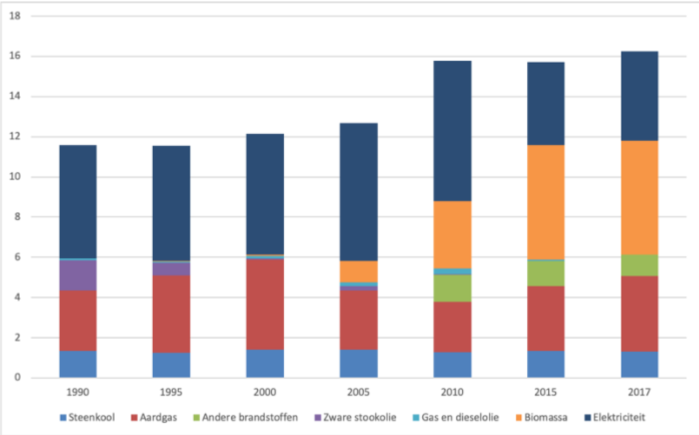

Figure 33: Evolution of energy use in paper production in period 1990-2017 (PJ) (Source: VITO, 2019)

6.4 Socio-economic: Value added, employment, investments

Gross Value Added

Between 2005-2017, the GVA of the manufacture of paper and paper products in Flanders rose by 9% (from EUR 738 Mn to EUR 783 Mn). During the same period, the share of this sector's contribution to the Flemish GVA decreased from 0.46% to 0.34%.[36]

Employment

Employment decreased 16% between 2005 and 2018 (from 9,787 persons to 8,234 persons). Employment as a share of the total Flemish economy dropped from 0.40% to 0.29% in the same period.[37]

Investments

The paper and paper products industry, while being a relatively small sector, invested EUR 1.2 Bn between 2005 and 2017[38], or 0.5% of total investments in Flanders over that period.

[36] Source: NBB, n.d., Regionale rekeningen, A38, NUTS 2
[37] Ibid.,
[38] Minus the year 2013 for which no data was available.

7. Food and beverages in Flanders: A profile

7.1 Overview

The food and beverages industry in Flanders has around 30 companies covered by the EU ETS and includes biofuels production. The sector is very diverse with main GHG emitting producers being sugar, beer, potato products, soy products, milk and milk products, citric acid and bio-oil based biofuels. It is logically a major consumer of biomass as raw material input.

Most food production is located outside of large industrial clusters with a presence spread all over Flanders. The sector has seen important growth over the last decade, making it one of the larger GHG emitting and energy consuming industrial sectors in Flanders after steel, chemicals and refining.

7.2 Emissions

In 2019, the food and beverages industry was responsible for 5.4% (1.19 Mt CO_2-eq) of industrial GHG emissions in Flanders covered by the EU ETS.

The GHG emissions in the food and beverages industry increased 14% in the period 2005-2019 (from 1.04 Mt CO_2-eq to 1.19 Mt CO_2-eq) (Figure 34).

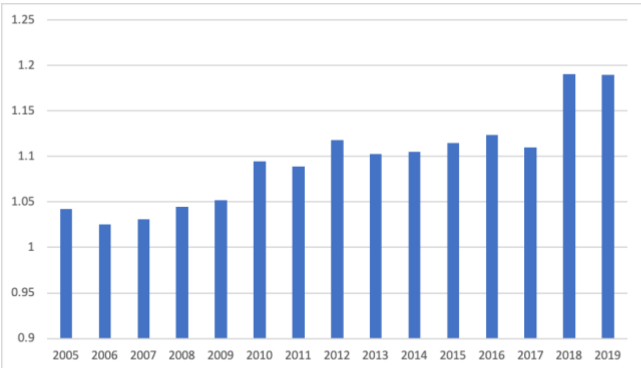

Figure 34: Evolution of GHG emissions of food industry under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

7.3 Energy

The final energy use of food and beverages production in Flanders rose 8% between 1990 and 2017 (from 38.8 PJ to 42.4 PJ). In this period the use of heavy diesel-fuel was reduced and replaced by higher use of natural gas. Today, natural gas and electricity form the main energy inputs for the food industry in Flanders.

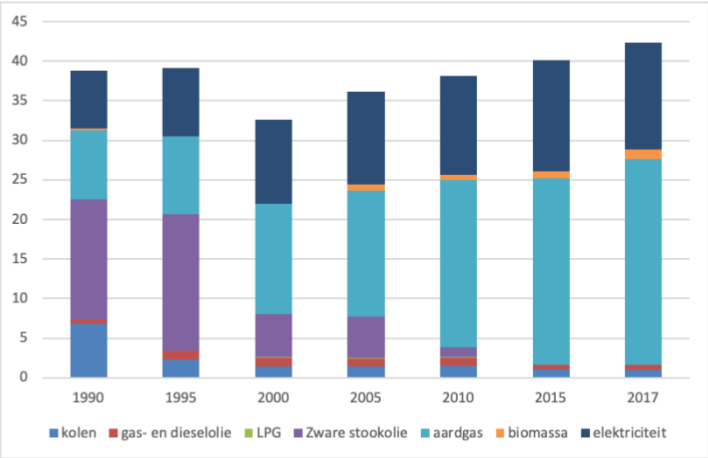

Figure 35: Evolution of energy use in food, beverages and tobacco production in period 1990-2017 (PJ) (Source: VITO, 2019)

7.4 Socio-economic: Value added, employment, investments

Gross Value Added

During the 2005-2018 period, the GVA of food, beverages and tobacco production in Flanders grew 32% (from EUR 4.6 Bn to EUR 6 Bn), the largest relative increase of any considered sector. However, the share of these sectors' contribution to the Flemish GVA decreased from 2.87% to 2.51% in same period.

Employment

Employment dropped 3.2% between 2005 and 2018 (from 70,345 persons to 68,089 persons). The share of employment to the total employment in the Flemish economy dropped from 2.87% to 2.41% in the same period.

Investments

The food, beverages and tobacco industry is the second largest industrial investor in Flanders having invested EUR 10.6 Bn or 4.6% of total Flemish investments between 2005 and 2017.[39]

[39] Minus the year 2013 for which no data was available.

8. Other sectors

8.1 Textiles production

The textiles production includes ten installations covered by the EU ETS in Flanders and is one of the smaller (emitting) sectors under the EU ETS. Textiles production covers yarns and fabrics but also and most importantly products such as floorcovering and carpets and other materials from basic chemicals. Most companies are located outside of large industrial clusters with important presence in West-Vlaanderen.

Emissions

The textiles industry is responsible for a very small share of industrial GHG emissions in Flanders, with emissions standing at 0.13 Mt CO_2-eq in 2019 or 0.6% of industrial emissions covered by the EU ETS in Flanders.

Between 2005 and 2019, emissions related to textiles production did decrease significantly (-26%)(Figure below), largely due to plant closures between 2007-2010.

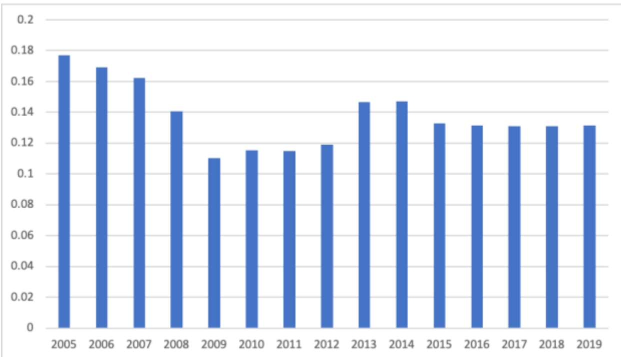

Figure 36: Evolution of GHG emissions of textiles industry under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

Energy Use

The final energy use of textiles production in Flanders followed a declining trend during the period 1990-2017, dropping from 17.4 PJ to 6.8 PJ or a decrease of 61% (Figure 37). Part of the reduced energy use is related to industrial closures happening after the year 2000. The main energy carriers used in the textiles industry are natural gas and electricity. Over the period 1990-2017 there was a fuel shift away from heavy diesel oil to natural gas.

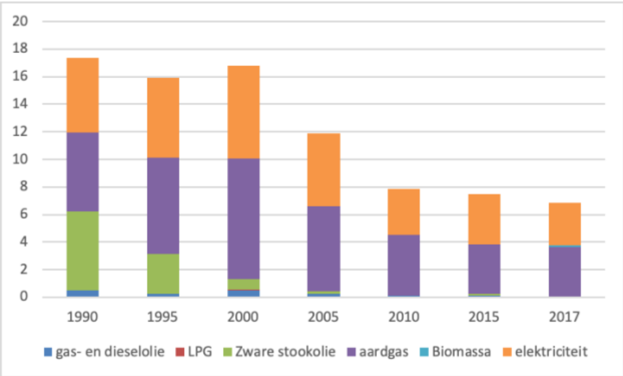

Figure 37: Evolution of energy use in textiles industry in period 1990-2017 (PJ) (Source: VITO, 2019)

Gross Value Added

Between 2005 and 2018 the GVA of the manufacture of textiles in Flanders decreased 33% (from EUR 1.8 Bn to EUR 1.2 Bn), the largest relative decline amongst all the considered sectors in this report. The share of this sector's contribution to Flemish GVA also decreased from 1.13% to 0.50% over same period.

Employment

Textiles saw the largest relative and absolute fall in employment out of all industrial sectors listed, with a decrease of 50% between 2005 and 2018 (from 36,835 persons to 18,579 persons). Employment as a share of the total employment in the Flemish economy dropped from 1.50% to 0.66% in the same period.

Investments

Even with a significant decline in GVA and employment over the past decade, the textiles industry still invested EUR 1.6 Bn or 0.7% of the total investments in Flanders between 2005 and 2017.

8.2 Glass and ceramics (part of non-metallic minerals industry)

Glass production in Flanders includes three companies covered by the EU ETS. Products include high quality glass for construction and glass (wool)-based isolation products.

Ceramics production includes 17 companies' sites covered by the EU ETS in Flanders. The sector's main output is aimed at construction with products such as bricks and rooftiles. Most ceramics installations are relative small greenhouse gas emitters (compared to other larger industries). Companies are located all over Flanders, with larger presence in north of Antwerp province. The main input material is clay, often locally sourced.

Emissions

The ceramics industry is responsible for a small share of industrial GHG emissions in Flanders, with emissions standing at 0.44 Mt CO_2-eq in 2019 or 2% of industrial emissions covered by the EU ETS in Flanders.

Between 2005-2019, emissions related to ceramics production did decrease significantly (-19%) (Figure 38), a key reason being plant closures which ensued between 2008 and 2010.

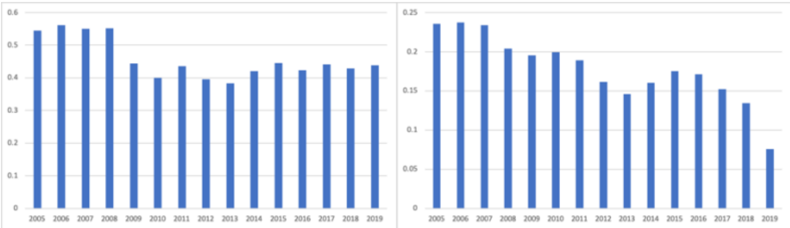

Figure 38: Evolution of GHG emissions of the Flemish ceramics industry [Left] and glass industry [Right] under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

The glass industry accounts for a very small share of industrial GHG emissions in Flanders, with emissions standing at 0.08 Mt CO_2-eq in 2019 or 0.3% of industrial emissions covered by the EU ETS in Flanders.

Between 2005 and 2019, emissions related to glass production decreased 68% (from 0.24Mt CO_2-eq to 0.08 Mt CO_2-eq), one reason being plant closures between 2007 and 2010 and a drop of emissions between 2018-2019 in a single plant, which is related to replacement of an old furnace. Hence it is better to compare the evolution of emissions in glass industry between 2005 and 2017, which was a reduction of 35%.

Energy Use

Ceramics and glass production are part of the non-metallic minerals industry, represented in 'De Vlaamse Energiebalans'. The non-metallic minerals industry registered an 9.5% increase in final energy use between 1990 and 2017 (from 14.5 PJ to 15.9 PJ) (see Figure below). Over the period the energy use increased between 1990 and 2005 and next (folliwng the economic crisis of 2008) went down again (with a drop of 7% between 2005 and 2017).

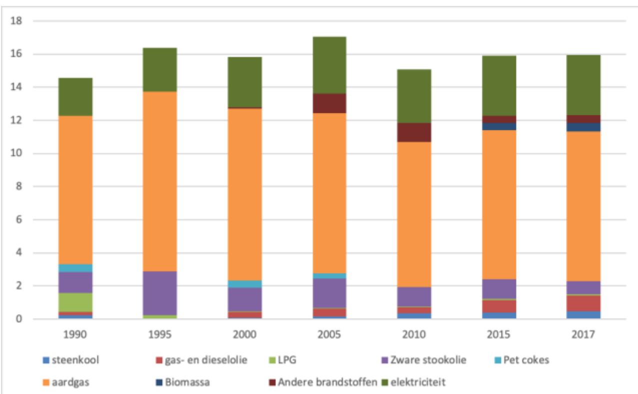

Figure 39: Evolution of energy use in Flemish non-metallic minerals industry in period 1990-2017 (PJ) (Source: VITO, 2019)

Gross Value Added

Between 2005-2017, the GVA of the manufacture of non-metallic mineral products in Flanders increased 18% (from EUR 1.2 Bn to EUR 1.4 Bn). The share of these sectors' contribution to the Flemish GVA however decreased from 0.73% in 2005 to 0.59% in 2017.

Employment

Employment in the sector fell 9% between 2003 and 2014 (from 17,001 persons to 15,524 persons) while the share of employment to the total employment in the Flemish economy dropped from 0.69% to 0.55% in the same period.

Investments

The non-metallic minerals sector invested almost EUR 2 Bn or 0.8% of total investments in Flanders between 2005-2017[40].

8.3 Non-ferrous metals (and metal products)

The non-ferrous metals and metal products industry, as defined under the EU ETS in Flanders, includes ten companies. These are companies active in the production of non-ferrous metals but also production of metal wires, cars and machinery.

The non-ferrous metals industry in Flanders is an important economic actor as part of the circular economy with major companies active in the circular economy using secondary raw materials e.g. electronic waste as input material with the goal to produce secondary copper, precious metals, rare earth and other metals. The sector is both energy- and electro-intensive (in particular the production of zinc). The sector's downstream value chain covers a large part of the manufacturing industry such as construction, automotive, electrical and electronic appliances and increasingly economic activities related to a climate neutral economy such as batteries, electric vehicles and material for wind-turbines.

Non-ferrous metals production is located mostly in the Antwerp province.

Emissions

The non-ferrous metals and metals products industry as covered by the EU ETS is responsible for a small share of industrial GHG emissions in Flanders, with emissions standing at 0.48 Mt CO_2-eq in 2019 or 2.2% of industrial emissions covered by the EU ETS in Flanders.

Between 2005-2019, the emissions related to non-ferrous metals production and metal products under the EU ETS increased (35%) from 0.35 Mt CO_2-eq to 0.48 Mt CO_2-eq (Figure 40). Part of this increase is likely due to the change in scope under the EU ETS as from 2008.

[40] Minus the year 2013 for which no data was available.

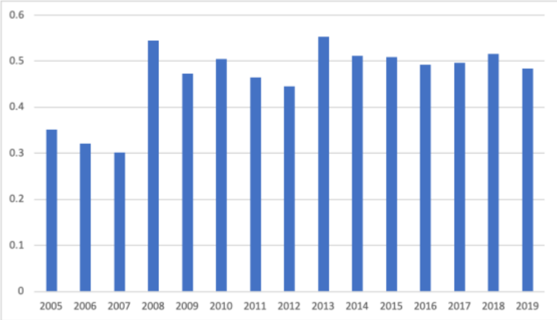

Figure 40: Evolution of GHG emissions of non-ferro industry under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

Energy Use

The metals (and metals works) industry as defined in the Vlaamse energiebalans registered an 18% decrease in final energy use between 1990 and 2017 (from 14.5 PJ to 12.5 PJ). In general, over the period 1990-2017 the energy use increased between 1990 and 2005 and next (following the economic crisis of 2008) went down (Figure 41).

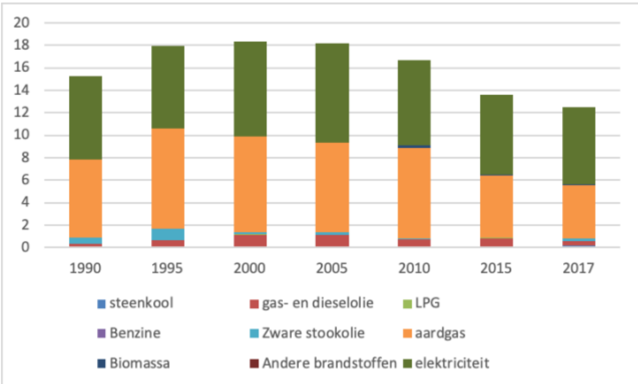

Figure 41: Evolution of energy use in Flemish metals (metaalververwerkende) industry in period 1990-2017 (PJ) (Source: VITO, 2019)

The socio-economic data for non-ferrous metals is included in the section on steel production.

8.4 Wood-products

Wood products are represented by four company sites under the EU ETS in Flanders. These produce materials for the building industry such as flooring and (fibreboard) panels. The main input material for this sector is wood. Part of the industry uses recycled wood for its products.

The wood-products industry is responsible for a very small share of industrial GHG emissions in Flanders, with emissions standing at 0.042 Mt CO_2-eq in 2019 or 0.2% of industrial emissions covered by the EU ETS in Flanders.

Between 2005-2019, the emissions related to wood products decreased (-8%) from 0.045 Mt CO_2-eq to 0.042 Mt CO_2-eq. Part of this decrease is likely due to change in scope under the EU ETS as from 2008.

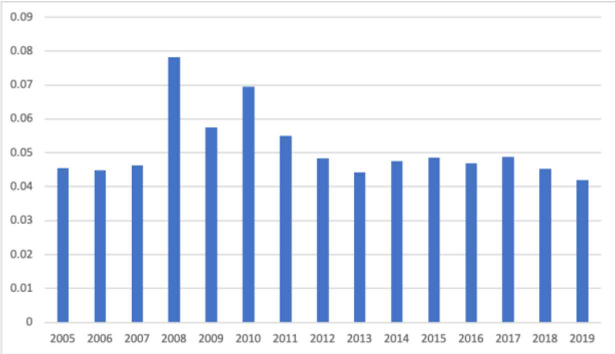

Figure 42: Evolution of GHG emissions of wood production industry under EU ETS (Mt CO_2-eq.) (Source: Vlaamse Overheid, 2020)

Gross Value Added

Between 2005-2017, the GVA of the manufacture of non-metallic mineral products in Flanders increased 5% (from EUR 0.63 Bn to EUR 0.66 Bn). The share of this sectors' contribution to the Flemish GVA however decreased from 0.40% in 2005 to 0.28% in 2017.

Employment

Employment in the sector increased 5% between 2005 and 2018 (from 9,736 persons to 10,202 persons) while the share of employment to the total employment in the Flemish economy dropped from 0.40% to 0.36% in the same period.

9. Technological options and R&D challenges for climate neutrality

This chapter provides an indepth assessment of technological options for deep GHG mitigation in chemicals, steel and refining industries; and an overview of mitigation options for the other industrial sectors. For the main technology groups the possible application in Flanders is discussed along with constraints and opportunities where appropriate. Next, a general strategic assessment is provided on cross-sectoral technology challenges.

The chapter further looks into industrial symbiosis and concludes by discussing stepwise pathways to climate neutrality. The assessments are based on a broad literature study together with emissions and energy data available for Flanders or calculated based on available data.

9.1 Chemicals industry

9.1.1 Introduction and approach

To assess GHG mitigation technologies for basic chemicals production in Flanders, the following approach is used. The main focus will be on technologies that have the potential to dramatically reduce emissions in large industrial process installations such as olefins, aromatics, hydrogen, syngas and ammonia production. In addition, technologies that can assist with high circular use of polymers (an important output of Flemish chemical industry) and bio-based polymers will be assessed. This will be followed by a broader techno-economic assessments of heat-and-industry-related energy technologies - currently the major source of GHG emissions in the chemicals sector next to process emissions. Next, CCS and CCU will be evaluated as a broader set of mitigation options for the Flemish chemical industry.

The result of the above-mentioned analysis will be summarised in a technology taxonomy for the Flemish chemical industry. Subsequently, an overview will be presented on outstanding technology and other challenges using the above-mentioned technology review and SUSCHEM’s recent strategic reseach and innovation agenda.

This chapter considers the following, sometimes overlapping, routes for low-CO_2 technologies:

- Low-CO_2 olefins and aromatics production
- Chemical recycling of polymers
- Low-CO_2 hydrogen, syngas and ammonia production
- Bio-based chemicals
- Low-CO_2 heat
- Carbon capture and utilization and storage (CCUS)

Some of the above applications will have a broader application beyond the chemicals industry (e.g. low-CO_2 hydrogen for refining or electrification and synthetic fuels for heat production).

9.1.2 Low-CO2 olefins and aromatics production

9.1.2.1 Introduction

In Flanders the production of olefins and aromatics predominantly happens via steam cracking of naphtha, increasingly together with LPG and ethane. Large quantities of propylene are also produced via propane dehydrogenation installations while aromatics are also an important by-product of crude oil refining. Over the next few years, additional olefins capacity is expected to be added via new ethane cracking and propane dehydrogenation units in the Port of Antwerp.

To evaluate the technologies, where possible, the benchmark for specific energy and GHG gas emissions will be evaluated against High Value Chemicals (HVC) production in process installations. High Value Chemicals are the collection of ethylene, propylene, butadiene and benzene, toluene and xylene (BTX).

In Flanders, HVC production via cracking and propane dehydrogenation uses approximately 74 PJ energy per year together with 165 PJ which is used as feedstock (2016 data). In total, this comprises 72% of energetic and non-energetic use in chemicals production.

This is around 3 Mt of CO_2 representing 34% of EU ETS emissions of the chemicals industry in Flanders.

Estimated HVC production (from steamcraking and propane dehydration) is around 5 Mt HVC p.a. in Flanders (consisting of estimated 43% ethylene, 32% propylene, 5% butadiene and 19% BTX).[41] Butadiene represents only a part of the C4 stream from cracking (not accounted as HVC).

As mentioned before, the HVCs form the backbone of chemicals value chains in Flanders, in particular but not exclusively for polymers production.

Main mitigation pathways for low CO_2 olefins, aromatics (and polymers) production are:

- New process technologies including use of catalytic processes, electrification and/or carbon capture (for utilisation or storage) and other feedstock e.g. methane
- Building up olefins and aromatics from CO_2 (e.g. via methanol or ethanol), including symbiosis with steel production via use of blast furnace technology
- Making olefins, aromatics and/or (new/existing) polymers via bio-based inputs
- Using polymer (post-consumer) waste as a feedstock for new olefins or polymerisation

[41] Own calculations using literature (includeing Ren, 2004, a for a model german steam cracker, and de Vlaamse energiebalans and emission data reported under the EU ETS

9.1.2.2 Naphtha steam cracking

Introduction
Steam crackers are among of the most technically complex and energy intensive installations in the chemical industry. It has equipment operating from -173°C to 1100°C and from near vacuum to 100 atmospheric pressure. The core of the process is the cracking of naphtha, LPG and/or ethane. This is an endothermic reaction which occurs in less than a second as the hydrocarbon mixture passes through tubes within the radiant section of the cracking furnace. The products are cooled rapidly (quenched) to prevent loss via side reactions and separated in a series of processes including compression, absorption, drying, refrigeration, fractionation and selective hydrogenation.[42] The end products of the process are ethylene, propylene, C4 chemicals includeing butadiene, fuel oil, pyrolysis oil incl. aromatics (such as benzene, tolluene and xylene) and gasoline, methane and hydrogen. In this report we consider ethylene, propylene, butadiene and benzene, tolluene and xylene (BTX) as the high value chemicals (HVC) output from steamcracking.

Using energy data in the Vlaamse energiebalans and installated production capacities, an estimate of 12-13 GJ/t HVC and around 0.6 t CO2/t HVC for Flanders was obtained. This is in line with figures found in literature.[43]

The main energy use in naphtha cracking relates to the pyrolysis of feedstock (75%, including steam production) with the remainder energy use for separation of products and other processes (25%). Electricity use is low compared to overall energy input.[44] In some cases excess steam from naphtha is exported to other processes (e.g 1.5 GJ/t HVC).[45]

Energy inputs are the by-products (e.g. methane, hydrogen, pyrolysis-gasoline) of naptha-cracking as well as methane or fuel gas in the case of refining.

Further efficiency improvements to existing installations are possible but limited, in particular given the high efficiency of steam-cracking in Flanders.

Catalytic cracking of light olefins
Catalytic cracking of light olefins (e.g. naphtha) can reduce the energy needs and hence the CO_2 emissions. A new advanced catalytic olefins (ACO) plant (by KBR) in Korea uses this technology at an estimated 10 GJ/t HVC and 0.4-0.5 t CO_2/t HVC. ACO technology produces propylene and ethylene in a 1/1 ratio and delivers a 10-25% higher olefins yield than steam cracking.[46]

Electrification of naphtha steam cracking
Electrification of naphtha steam cracking would be a major breakthrough given that it would eliminate most of the emissions from this process (-90%). However, electrification via retrofitting an existing heating unit, if theoretically possible, would be economically challenging. Assuming full

[42] CIES, n.d.
[43] Excluding the energy needed for the production of Naphtha. See: Ren, 2009, p.60.
[44] Ibid. ,
[45] Dechema, 2017, p.69
[46] KBR, 2013. This is a commercially available process so technology readiness level (TRL) is 9.

electrification of existing HVC production in Flanders at 12.5 GJ/t HVC and around 5Mt HVC, final energy use would mean 17.4 TWh (assuming full conversion of electricity in heat) additional electricity demand. This would equal more than 20% of the electricity demand in Belgium in 2018. Also, steam-cracking economics would not be straightforward, given that electrifying a cracker furnace does not imply lower input of naphtha because the yield of HVC's of around 70% from naphtha input would not change. The remaining 30% of cracking outputs are currently used to heat the cracking furnace. Hence electrification does not directly replace naphtha input but avoids the energetic use of cracking by-products. It will therefore be an additional cost unless the by-products can find a useful (and emission-free) application.

For electrification of steam cracking to succeed, a radical redesign of processes will be required which will increase the efficiency of the process and (related) higher yield of HVCs, avoid extreme high additional electricity demand, and lower generation of cracking by-products which cannot be used in the cracking furnace.

A 'cracker of the future' consortium has been set up between six companies, which have major cracking or dehydrogenation furnaces, with the goal to develop an electric cracking concept.

One of the technologies considered under this consortium is a new shockwave reactor design to be piloted in Geleen (Nl) by Coolbrook[47] after tests with a small reactor (90kg/h) proved successful.[48] The process would be based on accelerating naphtha in a turbine to supersonic speed and next via a counterturning turbine decelerate the naphtha to subsonic speeds and hence generate heat via the super-sub-sonic shockwave. In theory this approach promises to high energy efficiency and yields with 3-5 GJ/t HVC and 80% HVC yield. The engineering company claims that the cracker can be competitive at EUR 35-55 /MWh electricity price.[49] Assuming 3.6 GJ/t HVC electricity demand and 5 Mt HVC production, this would imply 5 TWh additional electricity demand in Flanders, if this technology would replace all incumbent installations.[50] Currently this technology is estimated to be at TRL 3-5. If the technology achieves successful piloting and demonstration phases it could reach commercialisation by 2035-2040.

An interesting side-effect and challenge of highly efficient electrification is how the cracking by-products will be treated. Assuming a higher yield of electric cracking and full replacement of heating with electricity, around 50 PJ of by-products become available. Valorisation of these without CO_2 emissions will be important in pathways to climate neutrality.

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[47] Coolbrook, n.d..
[48] Petrochem, 2020
[49] Energeia, n.d.,
[50] This would imply addition of around 1 GWe power capacity (assuming 90% availability).

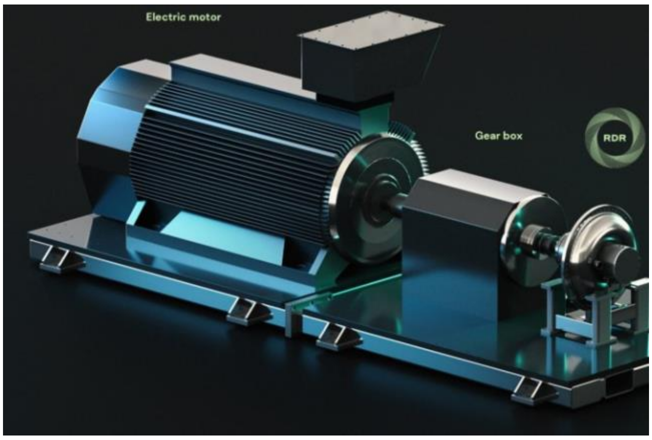

Figure 43: Electric cracker design. (Source: Coolbrook, n.d.,)

Capturing CO_2 from steamcracking
It is theoretically possible to capture CO_2 emissions from steam cracking furnaces but has not been put into practice commercially. The use of post-combustion technology of capturing CO_2 via mono-ethanolamine (MEA) was researched for a steamcracker in Sweden. The regeneration of the MEA absorbent would be the most energy intensive part of such a steamcracker with CCS with[51] 4.74 GJ/t CO_2 captured for the regenation of MEA (and endothermal process). The condenser of CO_2 rich flows uses another 1.78 GJ/t CO_2. In total this would mean an additional 6.5 GJ/t CO2 or (at 0.6 t CO2/t HVC) 3.9 GJ/t HVC produced. At 12-13 GJ/t HVC energy use this would imply an increase of 30-32% in energy for the production of one tonne HVC. The net capture cost was estimated at EUR 80 /t CO_2. Improved process integration could bring this down to EUR 55 /t CO_2.[52]

Carbon capture technologies are further discussed in section 9.1.7.1

9.1.2.3 Ethane to ethylene

Introduction
Steam cracking of ethane to ethylene has become more important over last years, in particular due to ethane recovery from shale gas. In Flanders a major ethane cracking plant is expected to become operational by 2023 (adding approximately 1 Mt ethylene production capacity).

State of the art ethane crackers have a specific energy use of 9 GJ/t HVC (assuming most HVC is ethylene) and have lower CO_2 intensity of 0.42 t CO_2/ t HVC compared to naptha steam cracking (due to the higher amount of hydrogen, a cracking by-product, re-used in the furnaces). The yield from ethane cracking is predominantly ethylene with a smaller fraction of propylene and hydrogen.[53]

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[51] Sherif, A., 2010, p. 15
[52] Ibid. p. 54
[53] Ren, 2009, p.60 and 63. Excluding the energy needed for the production of ethane and emission factor of 0.047 t CO_2/GJ energy input.

Electrification and capturing of CO_2

As with naphtha steam cracking, the electrification of ethane steam cracking will require process redesign to lower electricity needs and generate higher (ethylene) yields. In theory, direct electrification of burners in existing ethane cracking would have the advantage (compared to similar retrofit in naphtha cracking) of possible valorisation of larger volumes of hydrogen (which otherwise is used as fuel for cracking) that become available if not used in the cracker furnaces.

It is possible to use 'shockwave' reactor technology, such as the Coolbrook concept mentioned earlier, for ethane cracking[54]. As mentioned before, electric ethane cracking with a yield of 13% methane and hydrogen as by-product[55] could lead to direct and interesting valorisation of these two gases in other chemical processes.

Capturing CO_2 emissions from ethane cracking would face similar costs as naphtha cracking as discussed before.[56]

Innovative catalytic technologies

With regard to ethane cracking, interesting new catalytic processes are being researched which can significantly reduce the energy use and CO_2 emissions.

In the ethane *oxidative dehydrogenation (ODH)* route, ethane is selectively oxidized to ethylene and water. The removal of hydrogen as water pushes the system toward higher equilibrium conversions and the water product can be efficiently removed by condensation, lowering downstream separation loads. Energy use would be 5.85 GJ/t HVC, this includes additional electricity demand (compared to ethane steam cracking) from air separation units that deliver oxygen to the process. Specific CO_2 emissions would be around 0.3 t CO_2/t ethylene (assuming indirect emissions from oxygen production are avoided via zero emission power production).[57] While the process has been known for a while, it seems not to have moved beyond applied research at lab scale. TRL is hence estimated to be 3-4.

An alternative to the ODH route (which uses pure gas-phase oxygen) is to combine the catalyst with oxygen in a metal-oxide compound (MeOx), this is called a *chemical looping (CL) ODH* process. Circulating fluid bed chemical looping reactors use such oxygen transfer agents to promote chemical reactions. The oxygen transfer agent catalytically provides the oxygen to oxidize ethane to ethylene, producing water as the only major by-product. The oxygen transfer agent then reacts with oxygen (regeneration) in a stream of air, at the same time producing heat to support the reduction process. By avoiding an air separation unit, these reactors are net exporters of energy in contrast to the energy intensive conventional processes. Chemical looping reactors have traditionally been used in combustion-related applications, and with innovation, chemical looping oxidative

[54] Van Goethem, M., 2010, p.41
[55] Akah, and Al-Ghrami, 2015,. p.2
[56] While the emission intensity is lower in ethane cracking vis-à-vis naphtha cracking requiring less CO2 to be captured per tonne HVC, the CO_2 concentration in flue gases would be lower too making the capture process more energy intensive.
[57] Ren, et al., 2006, p. 441

dehydrogenation offers an opportunity to reduce the energy emissions footprint of production of ethylene from ethane.[58]

CO_2 emissions would be between 0.1-0.2 t CO_2/t HVC and energy use at 1.83 GJ/t HVC. The production costs could be 20% lower compared to conventional ethane cracking.[59] The low CO_2 emissions, lower energy use and production costs would make this technology very attractive if it becomes available. Futhermore, due to the low energy input requirements, electrification could be considered as an additional step, hence eliminating most the of CO_2 emissions.

TRL is estimated at 3-4 but CL-ODH is part of US ARPA-E funded research with goals to develop pilot plant over next years.[60]

Electrochemical conversion of ethane to ethylene
Ethane to ethylene conversion via electrochemical routes (e.g. fuel cells) is also being researched, but is at early R&D stage. Ethylene and hydrogen production via a proton-conducting electrochemical deprotonisation cell has been demonstrated at lab scale.[61] Compared to an industrial ethane steam cracker, the *electrochemical deprotonation process* can achieve a 65% saving in process energy and reduce the carbon footprint by as much as 72% or even more if renewable electricity and heat are used. If the heating value of produced hydrogen is taken into account, the electrochemical deprotonation process actually is claimed to have a net gain in processing energy.[62] The TRL is estimated to be low at 2-3.

Another similar but experimental concept is the *ethane to ethylene fuel cell* (e.g proton conduction ethane fuel cell (PC-EFC). This system would have the benefit of cogenerating ethylene together with electricity, while avoiding CO_2 emissions. This system has several specific advantages including high selectivity to ethylene and very little or no GHG (CO_2) emissions. In a proton-conducting fuel cell reactor, the dehydrogenation of ethane to ethylene and hydrogen (protons) is conducted over the anode catalyst, while the protons are conducted through the proton conducting electrolyte to the cathode side and reacted with oxygen to form water. Electrons are conducted through an external circuit during this reaction. This has been demonstrated at lab-scale with (90% ethane selectivity and) ethylene yields of around 40% (at reactor cell T of 750°C) and power density of 240 mW/cm2 (2.4 kW/m^2).[63] TRL is around 2-3.

9.1.2.4 Methane to ethylene

Other promising pathways for ethylene production consider the use of methane as a feedstock. This is interesting given the large scale availabitly of natural gas (incl. infrastructure) and its relative low cost.

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[58] Neal, et al., 2019,
[59] Estimate based on above id. p. 894
[60] Arpa-e, 2017
[61] Ding, D. et al., 2018, At a constant current density of 1 A cm−2, corresponding to a hydrogen production rate of 0.448 mol cm−2 per day, and 400 °C, a close to 100% ethylene selectivity was achieved under an electrochemical overpotential of 140 mV.
[62] Ibid.,
[63] Li, J. et al., 2011

Oxidative coupling of methane
Oxidative coupling of methane (OCM) has for years been seen as a possible economically attractive way of producing ethylene directly from natural gas with low additional energy inputs given the exothermic nature of the oxidative coupling reaction. Emissions related to energy consumption from the OCMOL process are inherently low because of its heat integration. Since oxidative coupling generates heat that can be used for reforming, no extra furnace needs to be installed. In theory, the only emissions that are related to energy are due to the consumption of electricity.[64] However, energy use to separate ethylene and other HVCs seems much higher compared to steam cracking. Futhermore, the reaction depends on the right catalyst to avoid side reactions that lower selectivity to ethylene and result in high process CO_2 emissions.[65]

The EU SPIRE MEMERE (MEthane activation via integrated MEmbrane REactors) project seeks to address these challenges by developing an integrated reactor and separation concept. Currently a prototype of the reactor is under development. TRL is estimated to be at 4.[66]

In 2015, Siluria Technologies started demonstrating the commercial scale production of fuels and chemicals made from clean, abundant natural gas. Siluria's breakthrough OCM process technology is believed to be the first commercially viable process to directly convert methane to ethylene. Specific information on energy use and GHG emissions for this plant has not been found. TRL is 7-8.[67]

Methane to ethane to ethylene fuel cell
As with the ethane to ethylene fuel cell mentioned before, converting methane to ethane and ethylene via a fuel cell has also been reported at lab scale. This cell uses a lanthanum-aluminum anode and a lanthanum-strontium-manganese cathode. The system achieved a reported 91% selectivity for ethane and ethylene (with the relative amount of these two products varying with temperature). But, at 1000°C, this fuel cell produces ethylene almost exclusively, with only trace amounts of ethane, CO, and CO_2. TRL is estimated to be 2-3.[68] [69]

Plasma assisted methane to ethylene (non-oxidative coupling)
Non-oxidative methane coupling is a reaction in which methane is turned into e.g. ethane and hydrogen or acetylene and ethylene without the oxidation of methane to CO or CO_2. Non-oxidative coupling can be done via a hybrid plasma catalytic reactor. In this process, a nanosecond pulsed discharge converts methane into acetylene at high yield (25%). Selective catalytic conversion of acetylene to ethylene would occur at no additional cost. Aside from the plasma initiation, no additional heat would be required for the hydrogenation. The system is self-sustained given that hydrogen is provided by plasma-assisted methane cracking. Data on energy use at large scale has not been retrieved.[70] TRL is estimated to be 2-3.

[64] See the EU funded OCMOL R&D project http://www.ocmol.eu/ocmol-process.html
[65] Ren, T., 2009, p. 69
[66] Gallucci, F., et al., 2018
[67] Siluria, n.d.,
[68] National Academies of Sciences, Engineering, and Medicine. 2016.
[69] Quddus, et al., 2010.
[70] Delikonstantis, E. et al., 2018,

Dry methane reforming to olefins
Dry reforming of methane is an indirect route of producing olefins from methane. First, methane and CO_2 are transformed into syngas. Next syngas gas can either be synthesised into methanol or dymethylether (DME). DME is a methanol equivalent and can be used as an intermediate to produce lower olefins like ethylene and propylene via the methanol to olefins route. The CO_2 that is produced in the DME process would be used in the dry reforming of methane and hence the overall process can be CO_2 neutral.[71] The synthesis of syngas to methanol is commercially mature (TRL 9) while dry methane reforming is at TRL 4-6[72].

Dry reforming of methane is further discussed in section 9.1.4 on hydrogen and syngas.

9.1.2.5 Propane to propylene

Currently, propylene is produced, next to production via steamcracking, through dehydrogenation of propane (PDH). In Flanders this production happens at one site but major expansions of this type of propylene production are expected over the next 5 years.

In PDH, propane feed is mixed with recycled propane and optionally also with recycled hydrogen gas and is fed into a heater to be heated to over 540°C and then enters the reactors to be converted at high mono-olefin selectivity. The reaction is endothermic. The propylene-rich reactor effluent is compressed, dried and sent to a cryogenic separator where hydrogen is recovered.[73]

The specific CO2 emissions of propylene production in Flanders are around 0.6t CO2/t propylene and specific energy use of around 8 GJ/t propylene[74].

Electrification of PDH furnaces can be considered, but, as in the case of ethane and naphtha cracking, it would need a radical reactor redesign to offset higher energy inputs. In case of electrification however, the large hydrogen co-production that is currently used in the PDH furnaces could be valorised in other ways. Similarly capturing CO_2 emissions (with low concentration of CO_2 in the flue gases) will require a significant amount of additional energy.

Propane oxydehydrogenation (ODH)
One alternative to PDH is the oxidative dehydrogenation (ODH) of propane, where addition of O_2 to the propane feed ideally produces propylene and water. Here, the challenge is to avoid further oxidation of propylene and hence formation of CO_2, which is favorable thermodynamically and often drastically reduces overall selectivity for propylene. Typical catalysts for ODH are vanadium, molybdenum, and chromium oxides. They still require relatively high operating temperatures in the 300–650°C range.

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[71] BASF, 2019
[72] Jarvis, and Samsatli., 2018
[73] Metso, 2018
[74] Own calculcations using publicly reported CO_2 data, installed capacity as mentioned in the GBPV permit. For estimation of energy use a yield (wt) of 86% propylene (literature based) per tonne of propane input, and assumption that hydrogen and other by-products from the dehydrogenation process were used in the furnaces.

The use of Metal Organic Frameworks (MOFs) is considered to improve the process, in particular by lowering the operating temperature to 200˚C. MOFs are materials built from inorganic nodes and organic linkers form extended periodic structures with well-defined, high porosity. They form small cages to immobilize the catalysts and hence improve the reactions.[75] Given the early stage of R&D it was not possible to provide an estimate on possible impacts on CO_2 emissions and energy use. As with the ethane ODH processes, the TRL is estimated to be low at 2-3.

Propane oxydehydrogenation with CO_2 (ODH + CO_2/CCU)b
Oxidative dehydrogenation of propane in the presence of CO_2 (ODPC) can be an attractive catalytic route for propylene production with less environmental footprint than the conventional oxidative dehydrogenation path with oxygen. Researchers have considered CO_2 as a mild oxidant that can overcome the problems of over-oxidation and low propylene selectivity, that are typically associated with the current synthesis routes. In the process, propane and CO_2 react over zeolites with transition metal oxides to propylene, water and carbon monoxide (CO).[76] Here also TRL is low at 2-3. Given the early stage of R&D it was not possible to give an estimate on possible impacts on CO_2 emissions and energy use.

9.1.2.6 Methanol to olefins and aromatics (CCU)

The methanol to olefins (MTO) and methanol to aromatics (MTA) processes with utilisation of CO_2 are seen as an interesting pathway for deep emission reductions in the production of olefins. The MTO process is commercially used (TRL 9) mostly in China and is highly CO_2-intensive given that the methanol synthesis uses coal as feedstock[77]. In Feluy, Belgium, Total built an MTO pilot plant for low-CO2 production of olefins.

The MTO reaction is (strongly) exothermic. The process follows a two-step dehydration of methanol to DME and water followed by the conversion to olefins. Depending on the catalyst, different target products can be realized such as propylene and gasoline.[78]

If the feedstock is a fossil fuel, the complete process would start with steam reforming followed by methanol production and finally the MTO. To produce one tonne of HVC's 2.83t of methanol is needed.

The MTA process is similar to the MTO mentioned before. Here methanol is converted to a range of aromatic compounds using a zeolite catalyst at 370-540°C and 20 to 25 bar. Compared to the MTO process the temperature is lower and higher catalyst acidity is required. Conversion is at 95–100% with an aromatics yield of 60–70 % of which 80% are BTX, resulting in a total BTX yield of 56%.[79]

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[75] Korzyńsky & Dinca, 2017
[76] Atanga, et al., 2018
[77] Fossil based olefins production via MTO is more GHG emission intensive and energy intensive compared to naphtha steam cracking. It would require 17.5 GJ/t HVC and emit 2.9 t CO2/t HVC (with naphtha steam-cracking in Flanders being 12-13 GJ/t HVC and 0.6 t CO2/t HVC respectively). While the MTO process in itself emits only 0.5 t CO2/t HVC the bulk of emissions are upstream in the (Steam Methane Reforming based) methanol production. Dechema, 2018, Low carbon energy and feedstock for the European chemical industry. p.
[78] Dechema, 2017
[79] Ibid.,.

The mitigation impact of MTO and MTA hence fully depends on the emissions or CO_2 utilisation related to the methanol production process.

The mitigation will be highest if methanol is produced using CO_2-free hydrogen. While the process itself emits 0.4-0.5 t/t HVC there is also 2.83 t Methanol needed to produce a tonne of HVC.[80]

To produce 1 t HVC, 3.9 t CO_2 would be needed.[81] Assuming 5 Mt of HVC production in Flanders, if MTO process would be exclusively deployed, would require 17.5 Mt of CO_2 feedstock (i.e. almost twice the current emissions of the chemical sector). This also assumes that CO_2 capture and H_2 production happens with zero CO_2 electricity and hence not generates additional indirect emissions.

The MTO pathway based on electrolysis-based hydrogen is very energy intensive. The energy (mostly electricity) required would be 95.5 GJ/t HVC or 26.6 MWh electricity per tonne HVC. Replacing Flemish olefins (5 Mt pa) with the MTO process would hence require 133 TWh electricity per year. This is almost double the current Belgian economy wide power consumption. The price for ethylene and propylene via this route is expected to be at least double of incumbent (steam cracking) production, but this depends to a large extent on the price of electrolysis-based hydrogen. A (very low) power price of EUR 10 /MWh and 80% capacity utilisation of electrolysers resulting in a methanol price of EUR 290 /t[82] would bring MTO in the range (but upper end) of EU ethylene market prices (around EUR 800 /t ethylene).[83]

Hence, essential factors that could make MTO-CCU more interesting are further innovation in clean hydrogen production with lower electricity consumption and at lower cost, more cost-efficient CO_2 capture and low, zero-CO_2 electricity prices (together with secure supply).

Next to the synthesis of methanol via hydrogen and CO_2 other options for low CO_2 methanol (to be used in MTO) are possible:

- *via natural gas-based syngas production with CCS*
- *via dry methane reforming*
- *out of steel waste gases (combination of H2, CO and CO_2)*
- *via syngas from biomass*
- *via syngas from municipal waste and post-consumer plastic waste*

Syngas production will be discussed in more detail in 9.1.4.

9.1.2.7 Ethylene via CO_2 and H2

It is in theory possible to directly produce ethylene or other olefins from hydrogen and CO_2 via an electrochemical pathway without the interim steps of methanol or DME synthesis. There is however currently no process at a

[80] The methanol production from captured CO_2 and H2 itself uses 1.372 t CO_2/t methanol and hence overall 3.888 t CO_2/t HVC is used. The net emissions (including the emissions in MTO process) are -3.4886 t CO_2/t HVC (or 3.5 t CO_2 is captured per tonne HVC produced). Calculations based on Dechema, 2017.
[81] Dechema, 2017
[82] Ibid.,
[83] Weddle, Nel., 2019

higher TRL which directly uses hydrogen and CO_2 to produce ethylene and other olefins.[84][85] While the general proof of concept has been shown, this technology is still at TRL 2-4.

Nevertheless, this technology would be a breakthrough and hence further research and development would be important to increase the likelihood of this approach becoming important in the future.[86]

9.1.2.8 Ethanol to ethylene (and propylene)

An alternative route to ethylene production goes via the dehydration of ethanol. The production of ethylene from ethanol dehydration occurs via acid catalysis.[87] The operating temperatures are between 180 and 500°C with conversions and selectivities depending on the operating conditions. The production of propylene occurs by the conversion of ethylene through a mechanism of oligomerization-cracking that requires temperatures above 350°C but favoring also the reactions of coke formation and the consequently catalyst deactivation.[88][89]

To produce one tonne of ethylene, 1.74 t ethanol is required. The energy input is 1.68 GJ/t (467 kWh/t) ethylene.[90]

The process of ethanol to ethylene conversion has been commercialised by Braskem.[91] TRL stands hence at 9.

Ethanol production routes considered later in this report are:

- biomass based: through sugar or starch-based biomass, lignocellulosis-based biomass.
- Via the fermentation of blast furnace gas from steel production (Steelanol)

A third option is the production of ethanol via CO_2 through the reverse water-gas shift reaction followed by the direct synthesis of ethanol. This would require 4.4 GJ thermal energy per tonne of ethanol and 36.9 GJ electrical energy per tonne ethanol for the production of hydrogen required for the reverse waters gas shift and ethanol synthesis. Production cost would around EUR 1000 /t ethanol.[92] The TRL is estimated at 3-4.

9.1.2.9 Conclusions on applying advanced low-CO2 olefins production technologies in Flanders

There is a wide variety of novel production methods for olefins with low-CO_2 emissions under development.

[84] Qin, T. et al., 2018
[85] Zhou et al., 2018.
[86] Dechema, 2017
[87] Catalysts used are zeolites (HZSM-5), aluminum silicates and aluminum silicates modified with transition metals
[88] Maia, et al., 2016
[89] Dechema, 2017,. p. 91
[90] Ibid.,
[91] I'm green, n.d.,
[92] El Fouih, & Bouallou., 2013

While most previous roadmaps on climate friendly olefins production tend to focus on CO_2 utilisation, use of biomass and to lesser extent electrification, recent research points to new catalytic processes with much lower energy and CO_2 footprints. These are definitely worth exploring further even if currenlty at low TRL.

Electrification of cracking processes has received more attention recently with announcements of chemical company consortia working together to develop this technology. Electrification comes with the benefit of reducing emissions from steam cracking by up to 90%. However, electricity demand will sky-rocket if all steam cracking in Flanders would be replaced by electricity-based steam cracking. Therefore R&D priority has to go to radical process innovations with electrification that significantly reduce the energy demand and lead to a higher yield. Even if in this case full electrification of steam cracking will still require high levels of electricity (almost 5 TWh more compared to today or the equivalent of 625 MWe power production capacity with 90% capacity utilisation). On the other hand, electrification will avoid the use of cracking by-products to feed the cracking furnaces. Full electrification would hence bring about <70 PJ (19.4 TWh) of by-products which will need to be used somewhere else without the release of CO_2 emissions. One option would be to use part of this by-product stream (e.g. methane, hydrogen, pyrolysis oil) in other low-CO_2 chemicals routes or energetically valorise them partially for power production with CCS (e.g. the Allam cycle) to cover part of the additional electricity demand. In any case, even partial deployment of cracker electrification will require strengthening both (low-CO_2) electricity production capacity and high voltage networks.

Carbon capture and utilisation for olefins production (e.g. via the methanol to olefins and/or aromatics route (MTO/MTA)) will depend on the availabilty of large volumes of new CO_2-emission free platform molecules such as methanol and ethanol. Large scale deployment of MTO/MTA will use huge volumes of captured CO_2 (almost 4t CO_2 for 1t of high value chemicals) but also hydrogen. Again, if low-CO_2 hydrogen is produced via electricity this will increase electricity demand significantly. However, molecules such as hydrogen, methanol and ethanol can be imported and hence reduce the strain on electricity production. In addition, other technological options presented in the next sections show alternative routes for low-CO2 methanol production e.g. via biomass, plastic waste recycling and natural gas with CCS. This would bring about additional flexibility in feedstock supply for MTO/MTA.

Finally, for new large steam cracker or propane dehydrogenation investments in Flanders planned over the next years, there will be a technology lock-in given that these installations are expected to operate until 2050 at least. These installations will not be able to apply the aforementioned options (most of which still at R&D stage) and will hence have to revert to carbon capture (and storage). Therefore, ensuring that these installations are designed to be forward compatible with CC(S) and have access to CO_2 transport infrastucture will be important part of the future transition pathways.

The conclusion is that for the climate transition of olefins production in Flanders no single pathway on its own seems optimal and hence a smart mix of electrification, novel catalytic processes, CCU and CCS will have to be implemented, while ensuring the adequate availabilty of enhanced electricity supply and new platform molecules and/or hydrogen which can either be domestically produced or imported.

9.1.3 Chemical and mechanical recycling of polymers

As mentioned in Chapter 3, polymers are a major product stream from the Flemish chemicals industry, closely linked with the production of organic chemicals such as HVCs. Plastics and plastic products export from Flanders were worth 23 Bn EUR in 2019 representing at 7% of the total flemish exports the 6th largest product group in all exports.

Dealing with plastic waste e.g. pollution in waterways and the sea has gained significant policy attention recently with the EU setting a 65% recycling target for municipal waste and a 75% recycling target for packaging waste by 2030.[93] This will increase the pressure to recycle more plastics. Given that non-EU countries have started to refuse accepting plastic waste originating from the EU, there will be more need for EU-based plastics recycling.

In Flanders the annual collected industrial plastic waste is over 200kt. The collected household plastic waste is around 70kt/pa. Around 140kt is imported (mostly from other EU countries). Around 35% or 140kt of all this collected waste is recycled, the rest (65% or around 270kt) is exported. There are 25 plastic recycling facilities in Flanders. Recycling happens mechanically with cleaned and sorted plastics being granulated or milled and next used in new products which either consist fully out of recycled materials or mixed with virgin plastic granulates.[94]

While the production of plastics via HVC's is energy and CO_2 intensive, with around 1t CO_2/t plastic produced[95], the end of life emissions of plastics have an even higher CO_2 footprint. Assuming an 80% carbon content of plastics full incineration at the end of life leads to around 3t CO_2 emissions. Currently most plastics that are not landfilled or spilled into the environment are incinerated (often with energy recovery). This is also the case for re-used or mechanically recycled plastics, though these extend the lifetime of the material. Increasing the mechanical recycling of plastics will remain important because it extends the lifetime of plastics and hence reduces demand for virgin polymers. It is also an energy efficient process. However, mechanical recycling does lead to downgrading of polymers and hence product quality and hence require the need of new plastic inputs.

From a life-cycle perspective it is interesting to avoid the incineration of plastics and use plastic waste as input for production of virgin plastic, hence replacing the need for fossil fuel based HVC's. This approach represents a group of technologies which falls under the scope of chemical recycling of plastics. It must be noted that under current climate policies and accounting of CO_2 emissions, a higher level of recycling and avoidance of incineration would not reduce the emissions in the industrial sectors covered by the EU

[93] European Commission, 2019a
[94] Vrancken, 2018; VIL, 2017
[95] Emissions from the conversion of crude oil to naphtha, the production of HVCs and the polymerisation of monomers.

ETS, because waste incineration falls outside of the scope of the EU ETS or even happens outside of Flanders or the EU (when plastic waste is exported).

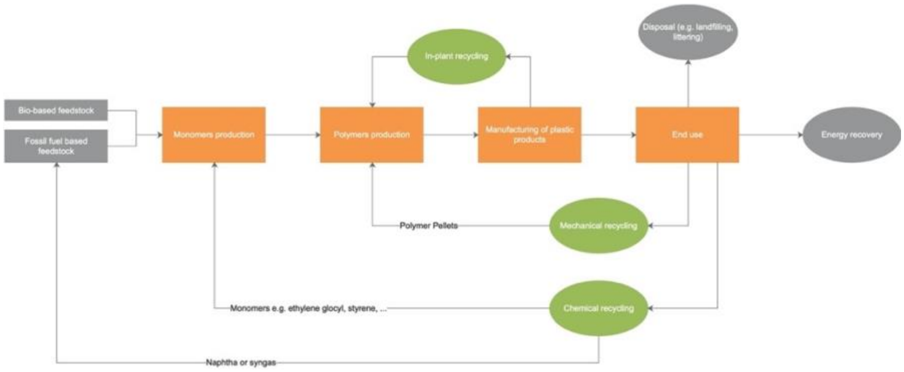

Figure 44: Simplified life-cycle of plastics

Chemical recycling in which plastic waste is recycled into monomer or petrochemical feedstocks will be an essential part of the reduction of emissions over the lifecycle of plastics.

Known processes for chemical recycling of plastics are:

- Chemolysis
- Pyrolysis
- catalytic cracking and hydrocracking.
- Gasification

In general, chemolysis of polymers will result in the monomers from which the polymer is formed (e.g. ethylene glycol and terephthalic acid for PET). However, not all polymers can be recycled via chemolysis. This is the case for e.g. polyethylene, polypropylene and PVC. Here, alternative chemical recycling routes such as pyrolysis or gasification must be followed.

To select the most interesting (non-chemolysis) route for chemical recycling, one needs to consider the apparent hydrogen-to-carbon ratio of the plastic waste content (the so-called gamma factor). Materials with a high ratio (e.g. PE, PP, PS, PU, PVC, ...) can best be treated via thermal cracking (pyrolysis) or catalytic cracking, while intermediate ratio waste (e.g. lignocellulosic materials) can be treated via gasification. The main logic behind this approach is that if materials with high ratio are incincerated, their hydrogen content would be lost via water.[96]

Chemolysis

Chemolyisis or solvolysis is the decomposition of polymers into their monomer parts. There are different depolymerization routes named after the solvents that assist the process such as methanolysis (methanol), glycolysis (ethylene glycol), hydrolysis (water), ammonolysis (ammonia), aminolysis (amines), and hydrogenation. Chemolysis can, in principle, be applied to PET, PU, PS, Polycarbonates and Polyamides (nylon). The

[96] Thunman et al., 2019

chemical recycling of PET is already applied at large scale (TRL 9)[97]. Chemical recycling of polystyrene (foam) has been demonstrated at pilot scale (TRL 7).[98]

Chemolysis happens at relatively low temperatures (100-300˚C) vis-à-vis pyrolysis and energy use in the process which, while not negligable, is significantly lower compared to virgin plastic production from naphtha or ethane.

Later in this report Polylactic acid (PLA) will be presented as an interesting biobased plastic alternative to polyethylene. It is worth noting that PLA can be chemically recycled through use of organic solvents.[99]

Pyrolysis
Pyrolysis is an interesting technology for plastic waste feeds that are difficult to depolymerize (via chemolysis) and that are currently not (mechanically) recycled but incinerated and/or dumped to landfill such as mixed PE/PP/PS, multilayer packaging, fibre-reinforced composites, polyurethane construction and demolishing waste.[100] Pyrolysis of plastic waste yields products (gas, liquids and solids), part of which can, with additional treatment, be turned into naphtha which can again be used in basic chemicals production as a replacement of crude oil-based feedstock. Polytetrafluoroethylene (PTFE), PA, PS and PMMA can be pyrolysed into products containing mostly their respective monomers.[101]

Pyrolysis of plastic waste remains an energy intensive process which takes place at moderate to high temperatures (500 ˚C, 1–2 atm) in the absence of oxygen.

Pyrolysis of plastic waste is a commercially available process (TRL 9). Innovative pyrolytic processes are less advanced, e.g. plasma pyrolysis (TRL 4), microwave assisted pyrolysis (TRL 4) and pyrolysis with in-line reforming (TRL 4).[102]

Catalytic Cracking (CC)[103]
The catalytic decomposition of polymers via FCC might offer better selectivity in yields of products vis à vis pyrolysis in addition to lower energy consumption. Depending on the catalysts and other process conditions used, the cracking products can be directed towards fuel, commodity chemicals and fine chemicals. Also, the use of catalyst allows the use of less stringent reaction conditions, lowering energy consumption of the overall process, and as such, affecting the total operating cost. At this moment several commercial catalytic processes are available (TRL 9).[104] They are

[97] Ragaert, et al., 2017
[98] PolyStereneLoop, n.d.
[99] Gironi, F., 2016
[100] Ragaert, K., Delva L., Van Geem K., 2017, Mechanical and chemical recycling of solid plastic waste
[101] Ibid.,
[102] Solis, & Silveira, 2020
[103] Miandad, R., et al., 2019
[104] Solis, & Silveira, 2020

however aimed at production of transport grade fuels such as gasoline or diesel.[105]

It expected that over the next decades, catalytic processes will become commercially available that give a large yield of high value chemicals out of plastic waste (with estimated maximum yield of 60% HVCs).[106] Current TRL is estimated to be 3-5.

Hydrocracking
The main difference with catalytic cracking of plastics and hydrocracking is the addition of hydrogen. This leads to a higher quality naphtha yield and opens the process for the use of a mixtures of plastics. The disadvantage of this process is the (energy) cost of hydrogren production and a challenging process operating environment (e.g high pressure). This increases both the OPEX and CAPEX.[107] TRL for this process is estimated at 7.[108]

Gasification
Gasification is one of the best-known technologies to convert a solid starting material whether pre-treated or not (e.g. solid municipal waste, biomass and plastics).[109] Gasification happens at temperatures of 700-1200˚C.[110] This process converts the plastic (or organic) waste feed, to a gaseous mixture containing CO_2, CO, H_2, CH_4 and other light hydrocarbons via partial oxidation. The process requires an oxidation agent, which is usually a mixture of steam and pure oxygen or air. The use of oxygen is preferred given its higher process effiency. However, this requires the use of an air separation unit (ASU) and increases the use of electricity.[111]

The syngas produced via the gasification of plastic waste can be used as feed for methanol synthesis. Methanol can hence be used in the methanol to olefins or aromatics (MTO/MTA) processes to develop the building blocks of new polymers.

Gasification technonology is commerically available (TRL 9). The more advanced plasma gasification is at advanced stage of technological development (TRL 8).[112]

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[105] Ragaert, et al., 2017
[106] Mastral, et al., 2001
[107] Ragaert, et al., 2017
[108] Solis, & Silveira, 2020
[109] Ragaert, et al., 2017
[110] Solis, & Silveira, 2020
[111] Ragaert, et al., 2017
[112] Solis, & Silveira, 2020

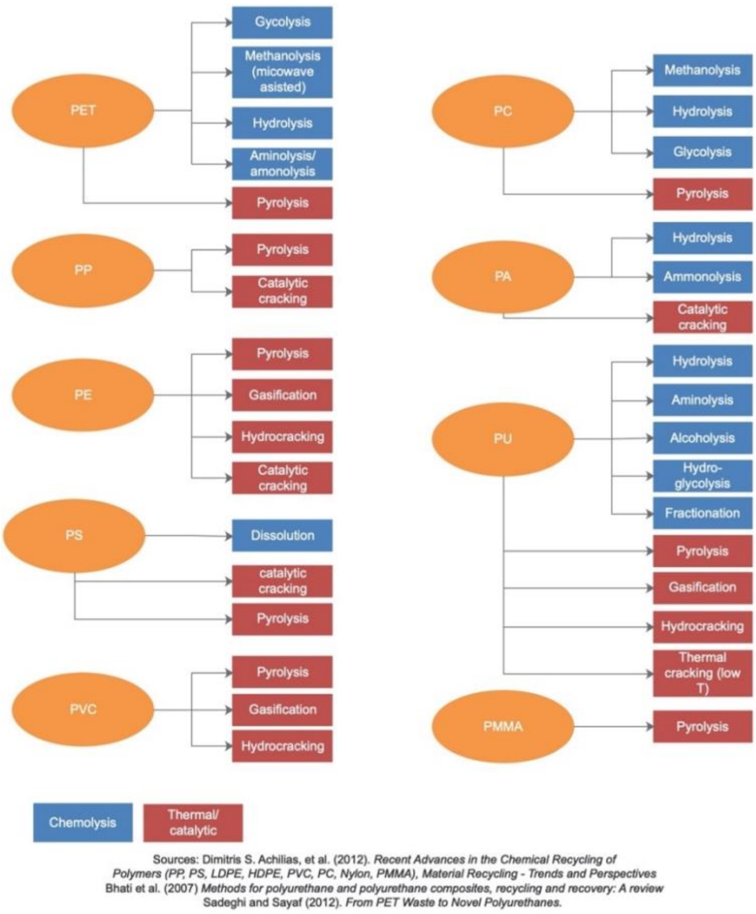

Figure 45: Options for chemical recycling for important polymers

Relevance for Flanders

From the perspective of feeding the extensive Flemish polymer value chains (from production of HVC's to polymers), it would be highly interesting and relevant to develop a large and mature chemical recycling industry tightly linked or even embedded in the current petrochemicals production, together with the further enhancement of mechanical recycling.

Chemical recycling could partially replace current refining industry-derived naphtha streams. Chemical recycling processes could directly provide monomers (for polymerisation), they can produce other HVC's (currently produced via naphtha or ethane steamcracking) and/or produce syngas that can feed the methanol to olefins or aromatics value chains. Furthermore, chemical recycling offers a solution for polymers that are difficult to recycle mechanically and hence are rarely recycled at all and end up in waste incineration. This would avoid a large part of emissions, albeit ensuing outside the EU ETS sectors and often outside of Flanders or the EU.

To become economically viable, chemical recycling will need to be applied at large scale and have access to a stable and adequate supply chain. This implies that plastic waste will have to be imported in significantly larger volumes than is currently the case (i.e. currently around 200kt/pa).

Furthermore, chemical recycling (in particular the pyrolysis, catalytic and gasification routes) does still require a large amount of energy and will come with CO_2-process and-energy related emissions. To ensure the GHG footprint of chemical recycling remains low, it would be important to ensure the capture and utilisation and/or storage of these CO_2 emissions.

9.1.4 Low CO2 hydrogen, syngas and ammonia production

This section considers technologies related to low-CO_2 hydrogen production. This includes hydrogen production as such but also the related syngas (i.e. a CO and H_2 mixture) and ammonia production.

In Flanders around 416 kt hydrogen is produced (approx. 50 PJ at 120 GJ/t H_2 Lower Heating Value (LHV)), more than 80% at the Port of Antwerp. The majority of hydrogen is produced by merchants (i.e. Air Liquide), followed by companies that generate hydrogen on site and hydrogen production as by-product of other processes.[113]

Carbon monoxide (part of syngas) is mostly used for the production of phosgene (in a reaction with chlorine) for use in polyurethane production.

Consumption of hydrogen predominantly occurs in ammonia production, and in hydro-desulfurisation (hydrotreater) and hydro-cracking processes in refining. In refining, hydrogen is provided through refining processes (catalytic reformer and where possible recovered from refining gas) but also via external supply from steam reforming.

Hydrogen use in chemicals production is dominated by ammonia production (via Haber-Bosch process) but is also used in other processes, e.g. in the production of hydrochloric acid and hydrogen peroxide.

Hydrogen will continue to be an important feedstock for industry, with the main challenge to make the production process CO_2 emissions free.

The transition of industrial sectors to climate neutrality will (significantly) increase the demand for hydrogen through the following technologies, processes and products (most of which are discussed in detail in other parts of this report):

- Low CO_2 synthesis of methanol via CO_2 and H_2. This methanol can be used as a synthetic fuel or (as mentioned before) in the methanol to olefins process.
- Ethanol production via the fermentation of blast furnace gas. This ethanol can again be used as a synthetic fuel or as feedstock for ethylene production via ethanol dehydration.
- In the conversion of CO_2 to naphtha or fuels via the Fischer-Tropsch process.
- As a replacement of coal/cokes as reducing agent in hot iron (steel) production
- For the production of other synthetic fuels such as dimethylether (DME), ammonia and acetic acid.
- In the production of synthetic methane (via the Sabatier process)
- For use in hydrocracking of plastic waste (chemical recycling)

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[113] François, et al., 2018, p.68

Below, three technology groups are presented:

- Methane based low-CO_2 hydrogen and syngas production
- Hydrogen and syngas production via electrolysis or photolysis
- Biobased syngas and hydrogen production

9.1.4.1 Methane based H2 and syngas production

Steam Methane Reforming (SMR) with carbon capture
Currently most hydrogen is produced via SMR. In steam methane reforming, methane reacts with steam in the presence of a catalyst to form H_2 and/or syngas (mixture of CO, CO_2 and H_2). Higher levels of H_2 are achieved through the water gas shift reaction (an exothermal reaction which oxidises CO to CO_2 while producing additional H_2). This results in higher concentration CO_2 off-gases which are removed via pressure swing adsorption (PSA). Next, CO_2 emissions can be processed for capturing.

Steam methane reforming is currently the globally dominant (almost single) process for H_2 production. The process is fed by methane (CH_4) with a total (energy and feedstock) consumption of 158 GJ CH_4/t H_2. The process emits 9 t CO_2/t H_2.[114]

Steam methane reforming produces surplus steam (around 4 GJ/t H_2) which can be used in other processes or utilities.[115] A new SMR-X process does not generate surplus steam and hence has a higher (internal) process efficiency.[116]

The high concentration of CO_2 process emissions makes SMR an interesting option for carbon capture. To capture 89% of the CO_2 emissions from SMR, resulting in 0.98 t CO_2/t H_2, the process would require around 14 GJ/t H_2 more energy.[117]

In principle there should be no technological barrier to deploy commercial scale carbon capture with SMR (TRL 7-8).

Autothermal Reforming of methane (ATR)[118] with carbon capture
This process is similar to SMR but uses pure oxygen instead of air in the combustion process. This results in higher concentrated CO_2 emissions which can be captured at lower costs. Additional energy is required however to provide oxygen (via air separation units) to the reformer.

ATR allows capturing up to 95% of CO_2 emissions, resulting in 0.64 t CO_2/t H_2. Around 124 GJ CH_4/t H_2 would be required together with 3.4 MWh electricity/t H_2 (for oxygen production).[119]

In principle there should be no technological barrier to deploy commercial scale carbon capture with ATR (TRL 7-8).

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[114] IEA, 2017a, p. 46
[115] Ibid.
[116] AirLiquide, n.d,a.,
[117] IEA, 2017a, p. 46
[118] The partial oxidation process (POX) process is similar to the ATR process with additional but lower level of oxygen added and without the use of a catalyst.
[119] van Capellen, et al., 2018

From a greenfield perspective ATR with carbon capture would hence be economically preferable over SMR and carbon capture.

Gas Switching Reforming (GSR) and combined cycle (CC) carbon capture
Gas switching reforming (GSR) is a promising technology for natural gas reforming with inherent CO_2 capture (up to 96% of CO_2 emissions). It is based on the principle of chemical looping reforming (CLR) in which an oxygen carrier material (usually a metal oxide) is used to transfer oxygen from an oxidation reactor fluidized by air to a reduction reactor fluidized by fuel gases. In this way, oxygen can be supplied to combust the fuel required to drive the endothermic reforming reactions while avoiding mixing nitrogen into the produced syngas stream.[120][121]

GSR has the advantage that it has the flexibility to switch between oxidation of methane for power production and reforming of natural gas for H_2 production. Hence, the technology seems well suited for integration in power systems with variable electricity production (with renewables such as wind and solar). The operator can choose to produce hydrogen at times of low electricity prices or to power generation at times of high demand and/or lower production from other sources.

The concept of GSR has been demonstrated experimentally (TRL 3-4) and system modelling shows it to be an economically attractive option for low-CO2 hydrogen production.[122]

Dry reforming of methane (CH_4+CO_2)
In dry reforming of methane, CH_4 reacts with CO_2 to form syngas (H2 and CO). This can be an interesting pathway for CO_2 utilisation and syngas production with use in e.g. methanol production. Thermodynamics for the dry reforming reaction are not as favorable as the ATR or even the SMR reactions.[123]

Around 200 GJ CH_4 is needed to produce 1 t H_2, in addition 17 MWh/t H_2 electricity (or other energy carrier) is needed to provide heat to the process.[124]

CO_2 Emissions from dry methane reforming are estimated to be very low under the conditions that the energy provided comes from (renewable) electricity and that the CO_2 that does not react in the reforming process is captured and circulated back into the process. Electrification of the process can be achieved through e.g. plasma-assisted dry reforming technologies.[125]

The main advantage of this process is the utilisation of CO_2. The resulting syngas can be used in the synthesis of methanol and next the MTO route for production of e.g. ethylene. Compared to methanol produced via

[120] Shareq et al., 2020
[121] Cloete & Hirth 2019
[122] Ibid.
[123] Lavoie, 2014
[124] Own calculations based on the stoichometry of the dry methane reforming reaction and assuming endothermal reaction requiring 247 kJ/mol CH_4. The process uses 11t CO_2 and 4t CH_4 to produce 14t CO and 1t H_2.
[125] Delikonstantis, et al., 2017

electrolytic H_2, much less electricity will needed and hence it can be an interesting technology in regions such as Flanders with relatively low natural gas prices and relatively higher electricity prices.

The TRL of dry methane reforming is estimated at 4-6.[126]

Methane pyrolysis
Methane (or other lower hydrocarbons) can be decomposed in a high temperature pyrolysis process generating hydrogen and solid carbon, without CO_2 emissions. The combustion of methane is a highly exothermic process generating heat whilst pyrolysis of methane is highly endothermic requiring the input of heat. Pyrolysis of methane is an equilibrium reaction, which begins to produce carbon and hydrogen at around 300°C and reaches maximum production at around 1000°C.[127]

To produce 1t H_2, 4.5t methane is required (225 GJ CH_4/t H_2). The reaction also results in 3.3 t carbon.[128] Around 19 GJ/t H_2 or 5.2 MWh/t H_2 energy is required.[129] [130]

Methane pyrolysis has not been piloted or demonstrated at large scale. TRL is hence estimated at 3-4.

Methane pyrolysis would, given its lower yield of hydrogen vis-à-vis SMR, only be economically viable if the carbon produced in the process is valorised. The most interesting application of carbon would be in steel production as a replacement of coal or cokes. This does still imply that the eventual CO_2 emissions in steel production would require further mitigation.

9.1.4.2 Electricity and photo-catalytic based H2 production

Electrolysis-based H_2 production is afast evolving domain with mature and close to mature technologies. Water electrolysis consists of three main H_2 production methods: alkaline electrolysis, proton exchange membrane (PEM), and solid oxide electrolysers (SOE).

Alkaline electrolysis
Alkaline electrolysis systems are the most commonly compared to other water electrolysis methods. The state-of-the-art industrial process for electrolytic hydrogen production uses a 20-40% solution of KOH, with Ni-coated electrodes as catalyst.[131]

Currently, 50-73 MWh-elec is required to produce 1 tonne of H_2 via alkaline electrolysis, or 46-66% (electrical) efficiency. By 2030 this is expected to evolve to 48-63 MWh-elec/t H2 (50-72% efficiency).[132][133]

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[126] Jarvis, & Samsatli, 2018
[127] Ozin, 2018
[128] Dechema, 2017, Low carbon energy and feedstock for the European chemical industry. p. 53-54
[129] Dincer, & Acar, 2018, p. 3–37.
[130] Assuming 37.4 kJ/mol H_2
[131] El-Shafee, et al., 2019
[132] Dechema, 2017, p. 48
[133] This is the electrical conversion efficiency, not the system efficiency which includees efficiency of power generation, transmission losses etc. In comparison SMR has an efficiency of 78% (120 GJ H2/154 GJ CH4), SMR with CCS an efficiency close to 70% (120 GJ H2/ 172 GJ).

Large scale electrolsyer installations currently have capacities up to 10 MW[134], but this is likely to be exceeded soon. Given the accelerated investments in alkaline electrolysers the CAPEX of these installations is reducing faster than expected. While studies in 2018 expected electrolyser CAPEX to move from around 500 USD/kW installed capacity in 2020 and to 400 USD/kW in 2030, there are indications that electrolyser CAPEX in China is already at 200 USD/kW with expectations that this will reach 115 USD/kW in 2030.[135]

Proton Exchange Membrane (PEM) electrolyser
PEM (Proton-Exchange-Membrane) electrolysis has been developed over the last 20 years and has now started to be commericially deployed (TRL 8-9). PEM runs on pure water (as oposed to the alkaline solution mentioned before) and is designed to run under high pressure (up to 100 bars). PEM electrolysis also demonstrates a very good dynamic behavior, which allows it to be integrated in electricity systems with high levels of variable (renewable) electricity generation.[136] [137]

Currently 47-73 MWh-elec is required to produce 1 tonne of H_2 via alkaline electrolysis, or 46-70% (electrical) efficiency. By 2030 this is expected to evolve to 44-53 MWh-elec/t H_2 (63-76% efficiency).[138]

CAPEX for PEM is estimated to be high (above USD 2000 /kW) in comparison with current alkaline technology, but this can be explained by the lack of large-scale investments and hence, for now, absence of technology learning curve. By 2030, PEM electrolysers, depending on the scale of investments over the next decade, could be below USD 500 /kW.[139]

Solid Oxide Electrolyser (SOE)
Solid oxide electrolysis (SOE) is the most electrically efficient but is still under development. Corrosion, seals, thermal cycling, and chrome migration are the major challenges faced by SOE technology.[140] TRL is estimated at 6-7.

SOE operates at a high temperature (up to 1000°C). This reduces the electricity requirements for splitting water into its elements. Currently, 37 MWh-elec is required to produce 1 tonne of H_2 via alkaline electrolysis, or 90% efficiency.[141] CAPEX is estimated to be still well above USD 2000 /kW but the technology has not been deployed at large scale yet and hence has not benefitted from technology learning curves.

This high temperature electrolysis is likely to work best in conjunction with large industrial processes that can deliver (preferably high temperature) surplus or waste heat.

[134] FCH, n.d.,
[135] Deutsch & Graf, 2019
[136] Dechema, 2017, p. 47
[137] El-Shafee, et al., 2019
[138] Dechema, 2017, p. 48
[139] Dechema, 2017, p. 48
[140] El-Shafee, et al., 2019.
[141] Dechema, 2017, p. 48

An additional possible benefit of SOE is that in certain configurations it can work in reverse as a fuel cell (RSOFC). This makes applications for grid balancing and power storage an option together with the production of hydrogen in the same module.[142]

Solid Oxide electrolyser cel (SOEc) using CO_2 and H_2O
An SOEc can also electrolyze CO_2 to CO. If water is electrolyzed at the same time (co-electrolysis), a mixture of H_2 and CO is produced. This syngas can hence be used in the production of methanol or (via fischer-tropsch) to other products such as synthetic gasoline, diesel or naphtha.

This type of SOE is still experimental with TRL estimated at 3-4.

Photo-electro(cata)lytic (PEC) hydrogen production
The PEC water splitting process uses semiconductor materials to convert solar energy directly to chemical energy in the form of hydrogen. The semiconductor materials used in the PEC process are similar to those used in photovoltaic solar electricity generation, but for PEC applications the semiconductor is immersed in a water-based electrolyte, where sunlight energizes the water-splitting process.[143]

Small scale demonstrations of this concept are in place at the moment with reported solar to hydrogen efficiencies of around 15%.[144] TRL is estimated at 3-4.

9.1.4.3 Bio-based syngas and hydrogen production

Syngas incl. hydrogen can be produced from biomass via gasification of biomass. It can also be derived from biogas via reforming. These routes are discussed in more detail in the section 9.1.5 dedicated to biobased chemicals.

Finally, hydrogen can be biogenically produced via photolytic biomass (e.g. photosynthesis). One example is the use of purple phototrophic bacteria that can use (human) sewage to produce hydrogen as part of waste-water treatment.[145]

9.1.4.4 Low CO_2 Ammonia production

Ammonia is mostly used in the production of fertilisers, but it is also an important feedstock in production of amines for e.g. caprolactam production and in urea and melamine production. In Flanders, the annual ammonia production is around 720 kt.[146]

Ammonia production takes place via the Haber-Bosch process where hydrogen and nitrogen (from the air) are forced to bind together at high temperature and pressure with the use of a metal catalysts. The reaction is

[142] Minh & Mogensen, 2013
[143] Office of Energy Efficiency & Renewable Energy, n.d.a
[144] KU Leuven, 2019
[145] Research Gate, 2018
[146] Calculated from permitted capacity (800 kt) and 90% capacity factor.

highly exo-thermic with excess heat (around 4 GJ/t NH_3)[147] often used for steam and/or power production.

Ammonia production comes with emissions of N_2O, a powerful greenhouse gas, almosts all of which can be catalytically removed. This is a commerically available and relatively cheap mitigation technology, currently applied in Flanders.

Per tonne ammonia around 1.3 t CO_2 process emissions occur and 0.6 t CO_2 emissions related to combustion.[148] The process emissions have a high CO_2 concentration given that CO_2 contaminates the Haber-Bosch process' catalyst and hence needs to be removed completely. Ammonia plants hence produce large flows of almost pure CO_2 gases, which are well suited for carbon capture and storage or utilisation (CC(U)S). The CO_2 is already captured, but needs to be compressed and transported to a storage (or utilisation) location.[149]

Ammonia production is an energy intensive process with around 32 GJ methane required per tonne ammonia, 1/3 of which is energetically used and the remainder used as feedstock for the process.[150] As mentioned before, the process does lead to surplus steam which can be used to power utilities or other processes.

Most of the emissions related to ammonia production take place in the hydrogen production phase via steam methane reforming. Hence mitigation of GHG emissions related to ammonia production will be similar to those discussed above in low-CO_2 hydrogen and syngas production.

Therefore, two main routes for low-CO_2 hydrogen production are:

- Steam methane reforming with CCS
- Electrolysis based hydrogen production

Steam methane reforming with CCS has been extensively discussed in chapter 9.1.4.1. For ammonia production in particular it has been estimated that up to 100% of the high CO_2 concentration process emisions (around 70% of the total emissions) can be captured at an (investment) cost of EUR 30/t CO_2.[151] At an ammonia price of EUR 350/t, this would imply a price increase of around 11% (assuming 1.3t CO_2 captured). While technologies needed to achieve capturing CO_2 from ammonia production are market ready, an integrated carbon capture ammonia plant has not as yet been established at large scale. Hence TRL is set at 7-8.

Producing 720 kt ammonia with electrolysis-based hydrogen would consume almost 7 TWh electricity (to produce around 128 t H_2 for the Haber-Bosch process).[152]

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[147] Batool & Wetzels, 2019
[148] Ibid.,
[149] Ibid.,
[150] Ibid.,
[151] Ibid., p. 33
[152] Based on Philibert, 2017,. p. 32 Assuming 0.178 t H_2/t ammonia and electricity: 40.2GJ/t ammonia

As mentioned before, solid oxide electrolyser cell (SOEc) technology, working at high temperatures, can be deployed more efficiently when linked to heat producing industrial processes. Hence it would be a very good electrolyser technology match for ammonia production.[153]

Electrolyser-based ammonia production can be cost competitive with natural gas-based ammonia production. Assuming an ammonia price of EUR 350 /t would require an electricity price of around EUR 25 /MWh to make electrolyser-based production (with electrolyser utilisation factor above 50%) cost competitive.[154]

A third, more innovative route would be the direct solid-state synthesis of ammonia. In Solid State Ammonia Synthesis (SSAS) NH_3 is produced directly from N_2 and H_2O, without intermediate steps. Direct electrochemical ammonia synthesis in molten-salt electrolytes and on membranes is under development. This could potentially reduce electricity consumption by up to 30%. The TRL of solid state ammonia synthesis is estimated at 3–5. Improvements are required into the ratio of NH_3 to H_2, material durability and conditions of operation (pressure and temperature).[155]

Ammonia with CO_2 can be synthesised into urea which in turn is the basic ingredient for the resin melamine. This process would be an example of CO_2 utilisation with fixation in a resin.

Ammonia can also be seen as an interesting H_2 carrier or synthetic fuel which can be combusted (e.g. shipping fuel) or used in a fuel cell (SOFC).

9.1.4.5 Discussion on relevance for Flanders

Based on the analysis in the previous sections, at this moment, the use of carbon capture (and storage or utilisation) has an advantage over hydrogen production via electrochemical processes. This is the case in particular for Flanders with relatively low natural gas and relatively higher electricity prices for industry. Natural gas and CCUS-based hydrogen production would in Europe see a price of around EUR 2 /kg. Currently, hydrogen production via electrolysers and renewable electricity would cost between EUR 2.7 and 6.7/kg (depending on the price of renewable electricity).[156]

Furthermore, CCS-based hydrogen production (assuming full storage) would have a much lower CO_2 footprint compared to electrolyser based production using the current CO_2 intensity of the power grid. With 89% capturing of emissions, the emissions per tonne of H_2 in SMR with CCS would be around 1t of CO_2. The emission factor of power production in Flanders (2017) was 0.26 t CO_2/MWh[157]. At 50 MWh per t H_2 via electrolysis, this gives 13 t CO_2/t H_2.

This situation will change! Between 2020-2030 the efficiency of H_2 production via electrolysis will increase and CAPEX will (rapidly) decrease.

[153] Philibert, 2017, p. 32
[154] Ibid., 33
[155] Amar, A., et al., 2011
[156] IEA, 2019
[157] Milieurapport, 2019

Furthermore, large volumes of cheap renewable energy will become available globally. This can make H_2 based on fully renewable electricity cost competitive by 2030-2035 and after that gradually the dominating form of hydrogen production. Main factors will be the development of renewable energy infrastucture globally, the logistics to transport it (to Flanders) either as hydrogen or as a hydrogen carrying molecule (e.g methanol or ammonia) and the continued investment in electrolyser capacity to maintain technology learning curves (and reduction in CAPEX).

Hence investments in SMR + CC(U)S-based hydrogen (incl. ammonia) production will need to happen in the short term (i.e. within the next years). This will result in the fastest reductions in GHG emissions and will reduces the risk of stranded assets at the time when renewable electricity-based hydrogen will become mainstream and highly competitive.

Methane pyrolysis for hydrogen production can be (in a limited way) considered in Flanders, if available by 2035, given the symbiosis with steel production (due to the use of carbon as the by-product of methane pyrolysis).

9.1.5 Bio-based chemicals

This section considers the production of chemicals which are based on feedstock (and energy) from biomass. The main focus is, as before, on high value chemicals and the production of polymers. The production of specialty chemicals from bio-based inputs is not directly considered here. While this is and will be an imported market for biobased products, the main scope of this report is the reduction of GHG emissions and focus remains on large volumes of high value chemicals, responsible for the majority of GHG emissions in the sector.

- bio-ethanol, bio-methanol, bio-naphtha and other bio-fuels
- bio-based HVC/aromatics (via lignin)
- bio-based syngas (incl. hydrogen) and methane
- bio-based polymers as replacement for fossil-based polymers

9.1.5.1 Bio-ethanol, -methanol, -naphtha and other fuels

The two main routes for bio-ethanol production are via sugar or starch rich biomass (e.g. sugar beets, corn or sugarcane) or via lignocellulosic biomass (wood, straw, …).

Bio-ethanol is currently moslty used as a biofuel (additive to fossil fuels) but can also be the feedstock for ethylene production via dehydrogenation.

Sugar and starch rich biomass to ethanol
Production of ethanol is basically based on the fermentation of sugar-rich biomass (such as sugar beets, sugar cane or corn), followed by distillation. The process first extracts the sugar from sugar rich crops (via heat-extraction and vaporisation). For starch rich crops (such as corn) the process requires hydrolisation first to mono-saccharides.[158]

[158] Dechema, 2017

This is followed by glucose fermentation, a mature process, and can produce ethanol at 92.3% yield, resulting in an overall biomass efficiency of 47.2% or 2.12t biomass for 1t of ethanol. Between 23.85 GJ/t ethanol and 38 GJ/t ethanol energy is required for the process.[159]

The process is deployed at large scale globally, hence TRL is 9.

Lignocellulosic biomass to ethanol
The pathway from lignocellulosis to ethanol is more complex. The starting point is biomass such as wood, wood and agricultural residues, grasses and straw. These contain, next to cellulose, also hemi-cellulose and lignin which have to be extracted and separated. This happens through hydrothermal treatment (high temperature and pressure steam) or via novel methods that use super-critical CO_2, a powerful solvent. Cellulose (and hemi-cellulose) is converted to sugars via enzymatic treatment. Next the latter can be fermented (via yeasts or bacteria) to ethanol.[160]

For wheat straw as feedstock, 6.75 tonnes are required to produce one tonne of ethanol. For wood this is 6.05t per tonne of ethanol. Previously it was shown that 1.74t ethanol is needed to produce 1t of ethylene via dehydrogenation. This brings the biomass input for 1t ethylene well above 10t. In the process, the recovered lignin is used as an energy source. Around 48 GJ energy is needed to produce 1t ethanol or over 83 GJ for 1t ethylene. This is very high compared to the naphtha and ehtane based routes discussed before.[161]

Lignocellulosic based ethanol production is not a mature technology yet but major demonstrations (e.g bio-refineries) are being developed, notably through EU funded projects.[162] TRL is hence set at 7.

Bio-methanol
Bio-methanol production from biomass starts with the gasification of biomass to syngas. The syngas is next fed into the known methanol synthesis process. Around 60% of wood-based biomass could be transformed into methanol. In addition, the energy use per tonne of methanol is estimated to be 14.6 GJ/t methanol. In total around 2.6t wood be required to produce 1t of methanol.[163]

The production of methanol from wood via gasificaiton has not reached maturity. TRL is estimated at 7.

Bio-naphtha
A novel method of bio-naphtha production has been proposed as alternative to bio-ethanol production for lignocellusosis. The catalytic process converts cellulosis pulp with addition of hydrogen into light naphtha.[164] The concept is promising given that it allows for the integration of biomass-based inputs

[159] The lower estimate requires the use of biomass residues from the process for energy production. Dechema, 2017
[160] Dechema, 2017
[161] Ibid.,
[162] ETIPBioenergy, n.d.,
[163] Dechema, 2017, p. 86
[164] Deneyer, et al., 2018

in the existing HVC value chains. Currently the concept is estimated at TRL 3.

Other bio-fuel routes
Currently the most important routes for biofuel (biodiesel and jet-fuel) production ensue via transesterification or hydrotreating of oil rich biomass such as rapeseed, soy and palm(oil) or from waste bio-oil (e.g. from frying).

Belgium produced (2014) around 18 PJ biodiesel and 12.5 PJ bioethanol as biofuels. The majority of production happens in Flanders and the overwhelming majority of production was intended for export.[165]

While the production is currently aimed at transport market it is also possible to connect the plant oil-based biofuels production to chemicals. For instance, via natural polyols to polyurethane, via fatty acid to longchain dibarboxylic acid (LCDA) to polyamides and glycerol to monopropylene glycol (MPG) to unsaturated polyester resin (UPR).[166]

Novel routes look at oil extraction of algae for the production of fuels (algal biofuels) and or chemicals. This has been demonstrated but at small scale.[167]

9.1.5.2 HVC's and aromatics via lignin and aromatics via C5 sugars.

Lignin, next to (hemi)cellulosis the major component of woody biomass forms the focus of multiple pathways to high value chemicals, in particular aromatics such as benzene, tolluene and xylene.

Biobased aromatics can be produced from lignin via thermochemical routes (gasification or pyrolysis) and via catalytic depolimerisation. In addition, aromatics can be produced from cellulosic derived C5 sugars via the Diels-Adler reactions. Lignin can also be used as the feedstock for phenol and propylene production.

A first pathway is to feed lignin (after de-oxygenation) to a cracker, where it has properties comparable to crude oil and will produce a kind of naphtha, containing a variety of aromatic compounds. This process is nearly operational today, although its cost-effectiveness is very much dependent on crude oil prices. TRL is estimated at 7-8.[168]

The second pathway is to produce BTX (benzene, toluene, xylene) catalytically from biomass or lignin in one step. This process is still in development.[169] TRL is estimated at 3-4.

Bio aromatics can also be produced via a direct route from sugars (extracted from lignocellulosis) via the Diels-Alder reaction giving furan and its derivatives. With the Diels-Alder reaction, aromatic compounds can easily

[165] Milieurappport, 2016
[166] Nova-institute, 2019
[167] Office of Energy Efficiency & Renewable Energy, n.d.b
[168] Biorizon, n.d.
[169] Ibid.,

be produced from furan derivatives. For instance, dimethylfuran will produce p-xylene when treated with ethylene.[170] TRL is estimated to be 4-5.[171]

Recently the concept of an integrated bio-refiniry was presented where lignin is transformed into phenol and propylene together with other phenolic byproducts. Around 60kg of propylene and phenol is yieled from 1t of birch wood. As part of an integrated biomass to chemicals production system this offers an interesting value proposition for lignin to HVCs. The TRL is estimated at 3.[172] Below it is suggested to consider the combination with lactic acid production from the cellulocic pulp in an integrated production concept.

9.1.5.3 Biomass-based syngas, pyrolysis and methane production

Biomass gasification
Biomass incl. biomass waste can be transformed into syngas via gasification. The syngas can next be used for production of e.g. methanol as input in the MTO/MTA process. The yield of hydrogen will not be as good as with methane SMR and the process does give unwanted byproducts such as char. Biomass gasification is a known technology (TRL 9).

A novel technology, close to commericalisation (TRL 8) is the reforming of biomass with supercritical water. Here the proces yields, next to CO and H_2, also methane (CH_4).[173]

Biomass pyrolysis
Biomass treated via pyrolysis will yield, next to gases such as H2 and CO, mainly oil type products which can be used as heating fuel, for transport or as starting point for production of chemicals.[174] TRL is estimated at 8.

Photolytic biomass
In photolytic biological systems, microorganisms—such as green microalgae or cyanobacteria—use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can be combined through direct or indirect routes and released as hydrogen gas.[175] The TRL is estimated at 3.

Biomethane
Biomethane is produced from biogas that is derived from organic matter such as sewage, food waste, distillery waste or agricultural materials via fermentation processes. In Flanders, the installed capacity for electricty generation from biomethane is around 134 MWe, delivering 665 GWh.[176] This is hence a commercially mature technology (TRL 9).

A novel concept for large scale methane production from biomass combines the gasification of biomass with a reformer of syngas to methane. Additonal H_2 is delivered via an SOE (that uses waste heat from the gasification process). The process requires around 30 GJ biomass and 11 MWh electricty

[170] Ibid.m
[171] European Commission, n.d.a
[172] Liao, et al., 2020
[173] Biomass Technology Group, n.d.a
[174] Biomass Technology Group, n.d.b
[175] Office of Energy Efficiency & Renewable Energy, n.d.c
[176] De Geest V., et al., 2015

per tonne of methane generated. [177] The total efficiency (energy in/methane out) is around 70%, which compares favourably to the e-methane route (discussed in section 9.1.6.). The combined TRL for this system is low at 3-4.

9.1.5.4 Other bio-based pathways to HVCs and polymers

This report only gives a limited overview of the multiple ways in which biomass can be used to produce chemicals. The main focus is on platform chemicals such as ethanol and methanol which can be produced in large volumes comparable to the current fossil-based HVC routes. Next to these routes, biobased inputs can also be transformed to amongst other things biocomposites (resins plus natural fibres), detergents, elastomers, surfactants, solvents, and cosmetics. While these products might not represent the high volumes of HVCs for e.g. polymers, they do represent value chains where value added can be much higher. Therefore, it must be stressed that while this report does not direclty consider these products this does not imply lower economic relevance.

Specifically, regarding bio-based polymers the global total production volume of bio-based polymers reached 7.5 million tonnes in 2018. This represents already 2% of the production volume of petrochemical polymers (348 Mt). The potential is much higher, but is currently hampered by low oil prices and a lack of political support.[178] Polyurethane produced via natural polyols (NOPs) represented the largest share of biopolymers (around 4 Mt out of 7.5 Mt) followed by cellulose acetate.

The flowchart below (Figure 46) gives an overview of the pathways from different types of biomass to polymers. This shows that almost all known fossil fuel-based polymers can (in theory) be produced via biobased inputs. But also new polymer types are present, some of which offer an interesting alternative to known and widely used fossil-based polymers. One example is PEF Polyethylene Furanoate which can be derived from 2,5-Furandicarboxylic acid (FCDA). PEF can be used as a very good substitute for PET.

Another example is polylactic acid (PLA) a polymer with similar properties to ethylene and applications in areas such as packaging. Lactic acid (LA) is produced via the fermentation of sugars such as glucose, sucrose and/or lactose. If lactic acid could be succesfully derived from cellulose, this could offer a very interesting alternative to the high-volume route via ethanol to ethylene. The latter requires up to 10t of wood for 1t of ethylene. On the other hand, a possible yield of almost 50% lactic acid out of wood has been reported.[179] Hence 2t of wood would yield 1t of lactic acid (and via polymerisation 0.9t PLA). Ideally LA would be generated via fermentation from cellulose but that seems challenging at the moment. It should be possible to develop micro-organisms that would facilitate this process. The TRL of this approach is below 3 at the moment. However, a cellulosis-based

[177] Clausen, 2017
[178] Chinthapalli, et al., 2019
[179] Wang, Y., 2013. Giving a LA yield of 70% from cellulose and assuming wood consisting for 70% out of (hemi)cellulose.

LA route could be combined with the lignin to phenol and propylene route mentioned above, increasing the yield of HVC(-equivalents) even more.

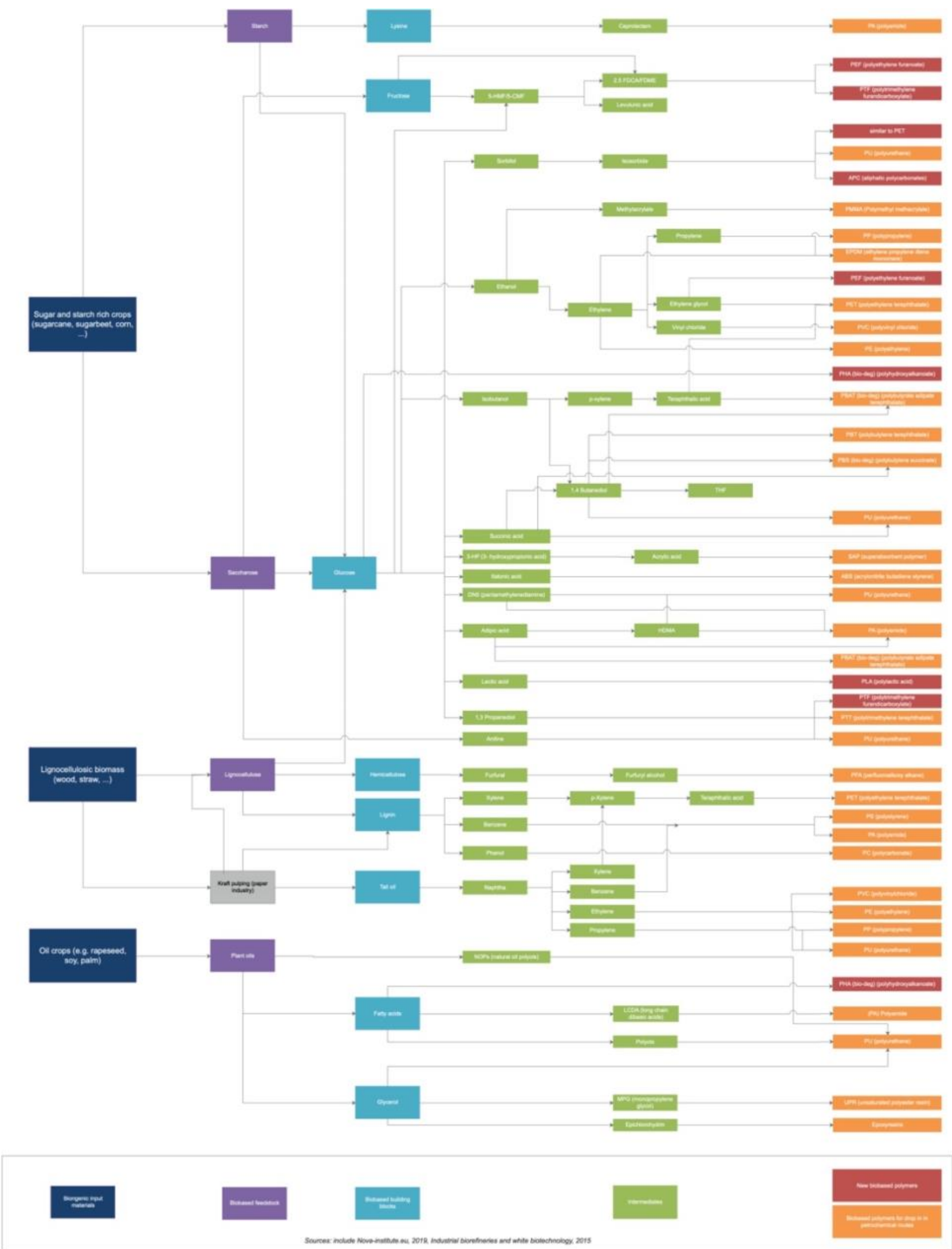

Figure 46: Taxonomy of biobased routes to polymers (main sources: Chinthapalli et al., 2019 and Pandey et al., 2015)

9.1.5.5 Discussion on role of biomass for chemicals in Flanders

As mentioned before, there are quite a few pathways towards bio-based chemicals. Given that in the future, high-volume production is expeced, leading to high demand for biomass, preference has to be given to biomass that cannot be used for food production. This implies that ligno-cellulosic biomass will become the main feedstock material for chemicals production. Ideally this biomass is sourced from straw, pruning of trees and bushes and forestry residues as to not compete with existing industries that use biomass to produce materials e.g. furniture and paper.

According the 'Atlas of EU biomass potentials' in a 2030 sustainability scenario more than 3000 PJ would be avaiable from straw (2000 PJ), pruning (370 PJ) and forestry residues (786 PJ). For Belgium the availabilty from the same sources would be limited to around 30 PJ in 2030.[180]

Producing 1 Mt ethylene (via ethanol) from cellulosic biomass (wood or straw) would require 10 Mt wood or straw and at 20 GJ/t biomass, this would be 200 PJ demand or 7% of the EU production of estimated availabe sustainable biomass in the EU by 2030. This demand is relatively high and will need to compete with demand from other countries and sectors that seek to switch to biomass-based materials production.

Hence it is recommended to further support R&D in biobased pathways that demand less biomass towards HVC or HVC-equivalent products. The cellulosis to lactic acid technologies are a notable example.

9.1.6 Low-CO_2 heat for industry in Flanders and link with power production

The previous sections focussed mostly on production processes for high value chemicals, including their energy use. While the total energy use (feedstock and heat) of these processes makes up around 80% of energy demand by the chemicals industry in Flanders, it is important to also consider the downstream energy demand for heat in the chemicals industry and other industrial sectors.

Using data from the Vlaamse energiebalans it is estimated[181] that around 322.3 PJ is used for heat in the industrial sectors (covered by this report) (2017). Per sector this gives:

- Chemicials: 112.5 PJ (of which 72 PJ delivered via fuels derived from processes)
- Food and beverages: 28.8 PJ
- Paper and printing: 11.9 PJ
- Non-ferro: 6.9 PJ, but this figure is likely higher given that part of electricity (not counted here) is used for heating purposes
- Ceramics and glass: 12.3 PJ
- Refining: 75.1 PJ (of which 49.9 PJ from refining gas)
- Steel: 74.8 PJ (+ 20 PJ of blast furnace gas exported to power production) but the use of coal and cokes is predominantly for the iron ore reduction process.

When excluding the use of recovered fuels and coal and cokes for steel production, the main fuel source in most sectors is natural gas (109.2 PJ in 2017). Combined heat and power installations are widely used in industry (incl. refining) in Flanders generating 2.94 TWh electricity and 26.4 PJ heat in 2017 (8% of the above-mentioned heat demand).[182]

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[180] Elbersen et al., 2012
[181] By looking at the energetic demand for industry and subtracting the use of electricity.
[182] VITO, 2019

This section will consider novel technologies that can assist with providing deep GHG emission reductions for furnaces, steam or other heat production. While not directly within the scope of this report, this section will also consider technologies for electricity production or storage where there could be an obvious symbiosis with industrial production processes.

The following technologies are considered below:

- electrification of heat
- e-fuels and biofuels
- use of low T heat integrated steam networks
- industry and power sector symbiosis (storage and demand response)
- carbon capture

Electrification of steam-production and boilers

Electrification of boilers is an efficient way to produce hot water or steam. But also, the investment costs of electric boilers are low. However, from an OPEX perspective wit low natural gas and relative higher electricity prices it is at this moment not an attractive direct mitigation option. However, given the low investment cost it is worth considering investing in hybrid-systems with electric boilers that can be switched on at times of low or even negative electricity wholesale prices. Full electrification of natural gas-based steam production in industry would require around 28 TWh electricity (around 1/3 of current total Belgian power production).

Hybrid-CHP provides a double flexibilisation effect: In times of low electricity prices, electric boilers may supply the steam. The CHP on the hand can be shut down or be operated at partial load, which is economic because the low revenues for electricity sales at these times would not cover fuel expenses. Today, large electrode boilers available on the market typically supply steam below 200°C and are therefore suitable for district heating supply, the food or the paper industry. TRL for the larger systems is rated at 7.

According to calculations of the Wuppertal Institute for Germany, hybridisation of CHP could be cost-effective in 2030 assuming a mean electricity price of EUR 15-25/MWh for 2000 hours of the year and assuming reference steam supply costs of EUR 35/MWh. The question if such concepts will be viable in the future depend on the electricity generation mix with its related fluctuations in prices and of course also on the electricity price regime for CHP operators and industrial electricity users.

A second, more energy efficient way to produce steam based on electricity is the use of waste heat in a heat pump. Today, there are technologies available operating with 90°C waste heat (typical for the chemical industry) and increasing the level to up to 160°C. Chemical heat pumps (working at an efficiency of 50%) are being developped that could bring low T industrial exces heat to even higher temperatures. These installations are estimated at TRL 5-7. Due to the continuous waste heat supply in chemical parks and the lower specific electricity demand of a heat pump they are more likely to be operated 24/7 in the future than electrode boilers.[183]

[183] Schüwer and Schneider, 2018

High temperature heat (above 400°C to over 1000°C) for industrial applications (e.g. ceramics, glass, non-ferrous metals, steam-cracking) is an area of promising research with novel industrial technlogies such as microwave, induction, plasma and radio-frequency heating as possibilities. These offer much higher efficiency and flexibility vis-à-vis combustion-based heating. However, most are still at TRL 3-5.

Use of alternative fuels
With the development of methanol, ethanol and ammonia from hydrogen (and CO_2 for the fist two) more climate friendly e-fuels can become available to be used for heating industry. Again, their uptake will depend on pricing (in particular in comparison to natural gas prices) and hence the availability of very cheap hydrogen produced via renewable energy. It is hence likely that if applied widely in industry in Flanders these efuels will for a significant part be imported from regions with low cost production.

E-methane, methane produced from CO_2 and hydrogen via the Sabatier reaction, would be an interesting option given that it can use the existing gas grid infrastucture and would require no large investments or very limited adjustments in industrial steam boilers or CHP running on natural gas. However, the energy demand for production of e-methane is high (around 96.5 GJ/t e-CH_4) mainly due to the production of hydrogen needed. Hence e-methane prices could be (depending on the cost of electricity for electrolysis) multiple times (up to 10 times) that of natural gas, the (almost identical) product it seeks to replace.[184]

Biofuels can play a bigger role for industrial heat. In 2017 9 PJ energy use in industry came from biomass (while total energetic use in Flanders from biomass was 70 PJ).[185] It is possible that with higher levels of transport electrification, more biofuels originally used in transport might find their way to industrial applications.

Hydrogen itself can be used in combustion installations for steam production. This would be interesting if sufficient hydrogen is available at competitive prices (v.s. natural gas). However, transporting hydrogen over longer distances (e.g. shipping) is not straightforward and logistics (ships) are not yet in place to provide this service. It hence more likely that hydrogen derived fuels will be used first.

As mentioned before the Solid Oxide Electrolysers (for H_2 production) could in some configuration be used as fuel cells with excess heat production. This flexibility together with industrial heat (supply/demand) integration could make this technology well suited for integration in industrial clusters.

Optimisation of heat production and use in industrial clusters
Further (cost and efficiency) optimisation of heat production, in particular in large industrial clusters is possible through system integration and recovery of industrial excess heat.

[184] Dechema, 2017, p. 77-79
[185] VITO, 2019

In large clusters cross-company steam networks can be considered such as the Ecluse project in the Port of Antwerp.[186] Not only does such networks bring efficiency gains by replacing smaller boilers it can bring even better economies of scale when linked to carbon capture. Here large steam boilers feeding the steam network can be linked with large carbon capture installations. Therefore, less cost-effiecient investments in more and smaller CO_2 capture installations would be reduced in favour of fewer but larger capture installations.

There are large amounts of industrial excess heat available in theory. According to VITO[187], 5.5 TWh low temperature (<120˚C) and 5.5 TWh higher temperature (120-200˚C) excess heat (around 40 PJ) is available from refining and chemicals production in Flanders.

Finding smart and useful applications for this excess heat will be important. Options inlcude power production via (organic) rankine cycle, allam cycle (making use of supercritical CO_2), thermally generative batteries, (chemical) and (chemical) heat pumps[188] to bring low T to more useful levels for industrial processes. Dymbiosis between recovery of excess heat and carbon capture seems an interesting option. While carbon capture (post-combustion) requires a significant amount of energy (e.g. 2.5-7 GJ/t CO_2 or around 25 PJ to capture 5Mt CO_2) the capture process operates at relative low temperatures (100-140˚C).[189] Hence, large scale process optimisation by using excess industrial heat for use in carbon capture could become a major feature in large industrial clusters, knowing that around 40 PJ excess heat could be available

Link with power production
While the production of electricity is beyond the scope of this report, it is worth noting that synergies between industrial process and power generation will be important to consider in future economy wide energy system research for Flanders.

Currently, industry is an important electricity provider (autoconsumption) via CHP or use of waste gases in power generation (e.g. steel production).

Future options next to low-CO_2 CHP (e.g. with carbon capture or running on alternative fuels) can include:

- Molten salt batteries[190]: which offer the possibility of symbiosis with high temperature exothermal processes using salts to control the heat generated of these processes.
- Thermally regenerative batteries (TRBs) can convert this waste heat into electrical power. Thermally regenerative ammonia-based batteries (TRABs) as well as acetonitrile-based batteries, based on copper electrodes, have been developed to produce electrical

[186] Ecluse, n.d.,
[187] Renders, L. et al., 2015
[188] https://www.qpinch.com
[189] Johansson, D., 2013
[190] Blain, 2018

current from the formation of copper-ammonia or copper-acetonitrile complex, using waste heat to regenerate the process.[191]
- Flow-batteries[192] which require large volumes of specific chemical solutions and could hence be located at large industrial sites.
- Cryogenic Liquid air energy storage (LAES)[193]: Here air is liquified (at very low temperature) and heated at times of high electricity demand to power a turbine. Symbiosis with industry is interesting given the know-how in chemicals production of cryogenic processes and storage of liquid gases. Furthermore, the process can only achieve high efficiency if it can make use of free excess heat, which is available in industrial clusters.
- Power production via Allam-cycle CCS[194]: A new and efficient technology for power production with supercritical CO_2 as heat transfer agent. This allows for power production at efficiencies comparable with CCGT. This power generation can be located at an industrial cluster investing in carbon capture and transport infrastructure and hence be an option to provide some of the additional electricity demand in industry. TRL for this technology is estimated at 7.

Enhanced industrial demand response
A future power generation system will depend on variable sources and hence will benefit from programmable variation in demand. Industrial processes, especially when moving to higher levels of electrification, can provide an important service here. Some energy intensive companies and sectors are already active in demand response services (est. 3.3-6.6 GWe in the EU).[195] Sufficiently large demand response capacity in the EU could reduce the investment costs in e.g. back-up power generation capacity (and storage), which would be reflected in power prices. Energy intensive power consumers can use demand response to improve their business cases (e.g. by being rewarded for lower production during times when electricity prices are high or by increasing production when overall demand is low). While due priority should be given to industrial demand response, there exist economic and other constraints towards full deployment of the same. Demand response makes real sense when there is dynamic pricing. Today, a large part of the electricity price is fixed (taxes & network). Price flexibility should be set by the market. Demand-response is not straightforward especially when looking at some of the core processes. Some hurdles include: safety risk (some companies have to manage high risk processes/products and will never adopt demand-response, whatever the benefit), costs related to the manufacturing process and production losses (especially if production is continuous), risk that a sudden and unforeseeable shutdown of an equipment can create in relation to production processes (e.g. restarting production) on product quality and equipment and trade-offs between energy efficiency and demand response.

Further R&D in this area can help deal with finding the optimal balance between reduction of power consumption and productivity. In particular,

[191] The new TRAB technology can be applied to convert low-grade waste heat, which cannot be used for any other application, into power. The process increases the efficiency of the manufacturing industry and reduces its carbon emissions. It is estimated that in Europe alone, TRAB technology could generate about 6 TWh of electricity per annum. Wyns & Khandekar, 2019.
[192] Service, 2018
[193] Coyne, 2020
[194] Allam et al., 2017
[195] Eurostat, 2018 | Derived from final annual electricity consumption of energy intensive industries in the EU in 2016 of 581 T Wh requiring 66 GWe production capacity (not including grid and transformation losses).

utility scale projects will benefit from this instrument and PPAs will as such assist in bringing additional renewable capacity online.[196]

Carbon capture and use of CO_2 as heat transfer agent
Finally, and as mentioned implicitly before, capturing CO_2 is an option for industrial combustion processes. This will be low concentration CO_2 emissions and hence energy and costs will be higher vis-à-vis capturing CO_2 from processes such as SMR and ammonia.

As mentioned above, economies of scale can help bring down costs. For instance, through cluster-based CO_2 networks and more centralised utilities to capture CO_2. It will also require the smart use of industrial excess heat.

Finally, if CO_2 is captured and available in large volumes, it may be worth considering to use CO_2 instead of steam as a heat transfer agent to industrial processes. However, while promising in theory, this concept is still highly speculative.

9.1.7 Carbon capture, utilisation and storage of CO2 and relevance for Flanders

While capture and utilisation of CO_2 has been touched upon in the previous sections, this section will specifically look at technologies for capturing CO_2 and give an overview of the possible utilisation of CO_2. It finally also considers elements related transport of CO_2 and the possible locations for storage.

The carbon capture process starts with the removal of dust, sulfur-dioxide and NOX in the flue gases (in particular for combustion flue gases) followed by capturing technologies (which separate CO_2) and next purification via liquefaction. The temperature of liquefied CO_2 is about -25°C at an elevated pressure, and the purity amounts to 99.999% (vol.). The oxygen content after liquefaction is less than 5 ppm. This high purity makes the CO_2 suited for utilisation in industrial process.[197]

For CO_2 capture, it is important to distinguish between sources with low CO_2 concentration in the exhaust gas and sources with high concentration. For the latter the (energy) cost to capture CO_2 will be lower and hence these processes will be the first candidate for capturing CO_2. Most combustion processes (if combustion happens without addition of oxygen) have low concentrations of around 10-15% in the exhaust gases. Oil refineries have 3-13% concentration of CO_2 in exhaust gases. High concentration exhaust CO_2 processes are[198]:

- Hydrogen production (via SMR) at 70-90% CO_2 concentration.
- Ammonia production: close to 100% CO_2 concentration.
- Ethylene oxide production: 30-100% CO_2 concentration
- Iron and steel: 15-30% CO_2 concentration

[196] Wyns & Khandekar, 2019
[197] Concawe, 2019
[198] Van Dael, 2018

- Bio-ethanol production: 100% CO_2 concentration

In Flanders, a rough estimate of the emissions from high concentration CO_2 source mentioned above (except steel) would be around 2.5 Mt CO_2 (est.). In one ethylene oxide production plant, the CO_2 is already being captured and used in other sectors.

Given the options to use CO and CO_2 in blast furnace gas in steel production [see steel sector Chapter 9.3] capturing and separating CO_2 emissions in steel production in Flanders will be important. The production of ethanol via fermentation of the blast furnace gas (steelanol) has the benefit that it comes with a high concentration CO_2 stream, which is almost capture ready. Depending on the fuel shift (e.g. biomass and hydrogen) applied to BF-BOF steel production, between 5-7 Mt CO_2 (est.) can be captured from steel production in Flanders (assuming part of blast furnace gas is not any longer combusted for power generation).

For the refining sector, carbon capture will be the main mitigation technology (next to efficiency improvements, electrification and use of low-CO_2 hydrogen). Assuming an 80% capture rate (which is ambitious), this implies 3-4 Mt CO_2 (est.) emissions to be captured from refining.

For the chemicals industry in Flanders, besides the above-mentioned (estimated) high concentrated 2.5 Mt CO_2 from ammonia, hydrogen and ethylene oxide; emissions from new large HVC production (e.g. ethane cracking, propane dyhydrogenation) will have to be captured (est. around 1.5 Mt CO_2). Additional capturing of CO_2 will depend on technology choices made for other process installations (e.g. bio-based, electrification). Chemical recycling (except for chemolysis) will lead to large amounts of additional CO_2 emissions, which can be and are preferably captured. For large combustion installations the use of CO_2 capturing will depend on the types of technologies applied together with possible fuel shifts (bio-fuels, e-fuels, hydrogen).

For sectors outside large industrial clusters (e.g part of paper, ceramics, non-ferro, food, …) carbon capture does not seem viable given the cost of infrastructure.

The technology readiness for carbon capture in industry is hard to estimate. The most advanced are the high concentration sources (e.g. ammonia and ethylene oxide) with proven capture technologies currently applied (post-combustion amine capture) at TRL 9. CO_2 from Ethylene oxide in particular is being captured at this moment and hence mature. End to end capture for ammonia production will be close to TRL 9. For steam methane reforming with CCS (currently TRL 7-8) the step towards TRL 9 will be small given the similarities with ammonia production. For lower concentration sources and steel production it might take up to 5 years for large scale demonstrations to be fully in place followed by commercial scale application around 2030. At a more detailed level, the capture technologies too are evolving with more efficient techniques (lower OPEX and CAPEX) becoming gradually available over the next decades. The global roll-out of industrial carbon capture will determine the speed of the learning curve and hence possible cost reductions.

From the perspective of timing, it is hence most likely that carbon capture starts with the easiest high concentration sources and from ongoing projects in steel production (steelanol). This will depend on the presence of necessary infrastructure to capture, transport and (at first) store the CO_2. If announced projects such as Antwerp@c proceed as planned, large volumes of CO_2 (min. 2.5 Mt) can be captured and stored annually before 2030 in the Antwerp cluster. For lower-concentration CO_2 sources, capturing is theoretically possible by 2030 but will require more expensive and complex investments. It is more likely the latter are scaled up after 2030, especially if some of the promising and more cost-effective capture technologies reach TRL by then.

9.1.7.1 Carbon capture technologies

Carbon capture represents a broad group of technologies. Below an overview is given for possible carbon capture technologies grouped as:

- Pre-combustion
- Post-combustion
- Oxyfuel

For the processes considered in this report it will be mostly the pre- and post-combustion technologies that will be relevant. Oxyfuel combustion sees more possible applications in power generation.

Post-combustion technologies
In the post-combustion process, the CO_2 is separated after the combustion. Technically, it is hence possible to retrofit existing installations with post-combustion capture technology. The flue gases are directed from the stack into the capture process, where the CO_2 is absorbed from the flue gases in a solvent, usually aqueous amine and then, by applying heat, desorbed from the solvent to obtain a pure CO_2 stream. Operational costs and energy costs are mostly related to the production and replacement of solvents and the energy needed to recover or scrub the CO_2 from the solvent.[199] [200]

Existing methods and novel prospects for post-combustion CO_2 capture include:

- Amine based (e.g. monoehtylanolamine (MEA)diethanolamine (DEA))
- Chilled ammonia
- Cryogenic separation of CO_2, which is promising with regard to energy required per t CO_2 captured.[201]
- Use of membranes
- Calcine looping
- Use of Metal Organic Frameworks (MOF)
- Electrochemical assisted capture (e.g. electrochemical swing processes).

This technology offers promising elements such as conversion independent of the initial CO_2 concentration and energy use at 1 GJ/t (TRL is 3-4).[202] [203]

[199] Sherif, 2010
[200] ter Telgte, 2012
[201] Song et al., 2019, p. 265-278 and AirLiquide, n.d,b.,
[202] Green Car Congress, 2019
[203] Voskian & Hatton, 2019

Pre-combustion technologies

Pre-combustion is a process that treats the fuel before the combustion e.g. as part of a chemical process. An example is gasification of carbon rich materials. Gasification is an endothermic process that converts a fuel to synthesis gas (CO and H_2) in lean oxygen conditions. Other products formed are mainly CO_2 and CH_4. The synthesis gas can then be used as a fuel or as mentioned in previous sections to make platfrom chemicals such as methanol. The gasification is often followed by the water-gas shift reaction (a shift to convert the CO and water to CO_2 and more H_2). Then the CO_2 is separated e.g. via pressure swing adsorption, the resulting pure H_2 stream can be burned in the combustion process. To obtain high purtity CO_2 one would still require treatment via one of the post-combustion processes mentioned above.[204] [205]

Examples are:

- Membrane shift reformer
- Autothermal reformer
- Sorption enhanced water gas shift (SMR/ATR)
- Gas Switching Reformer (GSR)
- Methane based Solid Oxide Fuel Cell with carbon capture (SOFC – CC)

Oxyfuel technologies

Oxy-fuel combustion is a process where the fuel is burned in pure oxygen instead of air. This reduces the volume of the flue gas since nitrogen is not present and therefore generates a flue gas with a high concentration of CO_2. Although, there are many advantages of this process the production of pure oxygen via air separtion units is energy consuming and therefore cost intensive.[206] However, next generation oxygen production routes will likely be using the more efficient membrane separation technology (TRL 5-7).[207] In the longer term, advanced oxy-fuel boilers and heaters are feasible, using an oxygen conducting membrane (OCM). OCM can produce high purity oxygen while reducing energy consumption (35-68%) and capital costs (35-48%) compared to cryogenic separation.[208]

[204] Sherif, 2010
[205] ter Telgte, 2012
[206] Ibid.,
[207] IPCC 2005, Allam et al. 2005
[208] ter Telgte, 2012

Figure 47: Taxonomy of (possible) carbon capture technologies. (Based on: Simeon, F. et al., 2010)

Direct air capture

The possibility of using so-called direct air capture (DAC) is now raised more frequently. This would be a capture process dealing with very low (atmospheric) CO_2 concentrations (410 ppm and rising or concentration of 0.04%). Capturing important amounts of CO_2 would require large volumes of air to be continuously treated/streamed. Today, two technology approaches are being used to capture CO_2 from the air at very small scale. The first uses liquid systems which pass air through chemical solutions (e.g. a hydroxide solution), which removes the CO_2 while returning the rest of the air to the environment. The second method, solid direct air capture technology makes use of solid sorbent filters that chemically bind with CO_2. When the filters are heated, they release the concentrated CO_2, which can be captured for storage or use. Between 6-8 GJ energy per t CO_2 captured would be required.[209] As the technology has yet to be demonstrated at large scale, the future cost of direct air capture is uncertain. Capture cost estimates reported in literature are wide, typically ranging anywhere from USD 100/t to USD 1000/t CO_2. Carbon Engineering, a company developing DAC recently 'claimed' that capture costs would be lower, to the order of USD 94/t to USD 232/t CO_2. But these are forward looking projecions depending on financial assumptions, energy costs and specific plant configuration.[210] Fifteen direct air capture plants are currently operational in Europe, the United States and Canada. Most of these plants are small.[211]

[209] These estimates are reported by the IEA based on claims by one of the main companies involved in commercialisation of DAC. Caution and a broader literature review are warranted given that these figures come close to the energy needs for industrial capture of CO_2 at concentrations at least 100 times higher.
[210] Keith et al., 2018
[211] IEA, 2020

Costs of carbon capture

Based on the findings in the previous sections, the energy to capture CO_2 for low-concentration CO_2 sources, such as steam crackers and combustion installations is estimated at around 5-6 GJ/t CO_2.[212] For higher concentration sources such as ammonia production the estimations stand at 2 GJ/t CO_2.[213] These energy costs next to the CAPEX will be the most important elements in the cost per tonne avoided CO_2. Finding good and specific estimates for carbon capture cost per sector is not straigthforward and different literature sources had to be consulted which do not apply the same methodology for calculating the cost of capturing CO_2. For the main processes considered in this report the cost to capture a tonne of CO_2 are estimated at:

Process	EUR/t CO_2 captured
Ethylene oxide	18.5 EUR/t CO_2[214]
Ammonia	20 EUR/t CO_2[215]
Steam Methane Reforming	37.1-59.8 EUR/t CO_2[216]
Naphtha Steam cracker	55-80 EUR/t CO_2[217]
Combustion (CCGT-natural gas)	62 EUR/t CO_2[218]
Steel production	70-90 EUR/t CO_2[219]
Refining	128.5-187 EUR/t CO_2[220]

Table 1: Overview of capture costs for selection of processes

9.1.7.2 *Utilisation of CO_2*[221]

In the previous sections the utilisation of CO_2 has been introduced for a number of processes. These are:

- Methanol and/or Dimethyl-ether synthesis from CO_2 and H_2
- Ethanol production from CO_2 and H_2
- Proprane oxy-dehydrogenation with CO_2
- Solid Oxide electrolysis with CO_2 to syngas
- Methane dry reforming (CH_4+CO_2) to syngas
- E-methane production via the Sabatier reaction (CO_2+H_2)

As mentioned before, for the production of large volumes of HVCs in Flanders via CO_2, the routes via CCU-based methanol to olefins or aromatics (MTO/MTA) seem at this moment in time technologically viable to start at large scale by 2030.

[212] Sherif, 2010p. 15 estimated 6 GJ/t CO_2 for steam-cracking. Petrovic & Solan, 2019 estimated 5 GJ/t CO_2 for CCGT.
[213] IEA, 2017b
[214] Summers, 2013 - USD to EUR at 2013 exhange rate 1.333 EUR to 1 USD
[215] Ibid.,
[216] IEA, 2017b. CO_2 avoidance cost minus 10 EUR/t for transport and storage
[217] Sherif, 2010, p. 55
[218] Rubin et al., 2015,. p. 5
[219] Duncan et al., 2014, p.23
[220] Cost for refining are notably higher due to the complexity of capture integration in refineries with large amounts of point sources. In these costs the cost for additional utilities are included. USD to EUR at 2017 rate. Roussanaly et al., 2017
[221] For exhaustive list see: European Commission, n.d.b.

Other options for CO_2 utilisation can be:

- Production of other fuels (besided methanol and ethanol) via Fischer-Tropsch process
- Replacement of phosgene by CO_2 in the process towards MDI and polyurethane
- The use of CO_2 in the production of polyols for polyurethane
- The current use of CO_2 for urea production and transformation of urea to melamine
- The use of CO_2 and CO via fermentation to ethanol (steelanol)
- Bacterial conversion of CO_2 to fuels
- Use of CO_2 in production of proteins (e.g. animal feed or animal protein replacement)
- Carbonation of materials for construction (e.g. cement, concrete such as the Carbstone product).

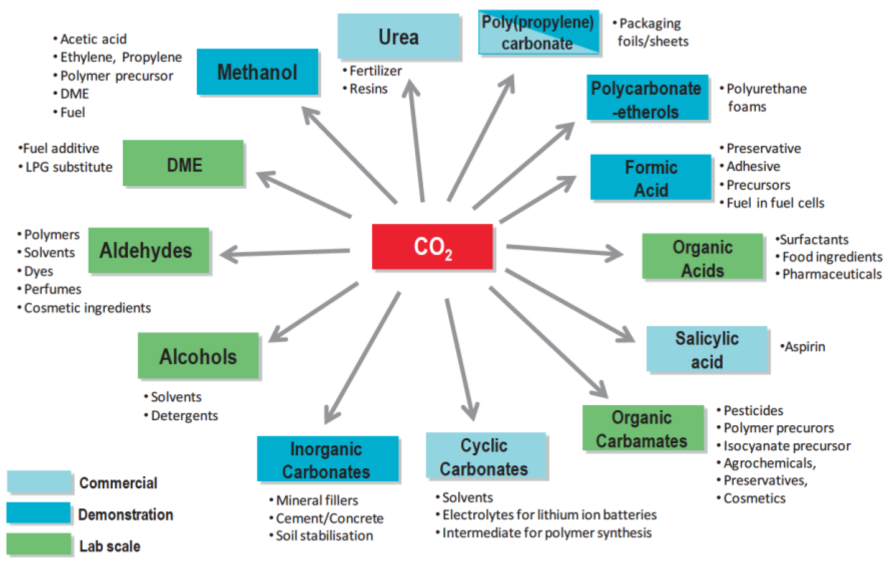

Figure 48: Possible applications of CO2 utilisation (source: Dechema, 2017)

9.1.7.3 Transport and storage of CO_2

Carbon capture and storage (CCS) is widely regarded as a key GHG mitigation technology that can capture up to 90% of the carbon dioxide (CO_2) emissions produced from for the power generation sector and other carbon-intensive industries. The CCS chain consists of three parts; the capture of CO_2 from emission point sources, the subsequent transport (via dedicated pipelines and/or ships) and storage in geological reservoirs (eg. depleted oil and gas fields and saline aquifers).

Captured carbon capture technologies have been discussed above. Captured carbon dioxide is transported in gaseous, liquid or, rarely, solid phase (but typically involves the compression of CO_2 into its denser or liquid form) by pipeline or by ship. Albeit pipelines are the dominant mode of transporting CO_2 given it is the most economical for transporting large volumes of CO_2, its ability to deliver a constant and steady supply of CO_2 without the need for temporary storage along a transmission route, and because the location of anthropogenic CO_2 sources and suitable sinks is typically away from navigable waterways.[222]

The carbon dioxide is then stored in carefully selected geological rock formation that are typically located several kilometres below the earth's surface with pressure and temperatures such that carbon dioxide will be in the liquid or 'supercritical phase'. Similar to how fossil fuels have been secured underground for millions of years, once injected, the CO_2 moves up through the storage site until it reaches an impermeable layer of rock known as the cap rock which traps the carbon dioxide in a mechanism known as "structural storage".

Although there exist thousands of kms of CO_2 pipelines in the US, the need to build such infrastructure is only recently picking up in Europe. The table below shows the existing pipeline network in Europe.

Project Name	Country Code	Status	Length (km)	Capacity (Mton/y)	Onshore/ Offshore	Sink
Sleipner	NO	O	160	1	Both	Porous Sandstone Formation
Snohvit	NO	O	15	0.7	Both	Porous Sandstone Formation
Peterhead	UK	P	116	10	Both	Depleted oil/gas field
White Rose	UK	P	165	20	Both	Saline Acquifier
ROAD	NL	P	25	5	Both	Depleted oil/gas field
OCAP	NL	O	97	0.4	Onshore	Greenhouses
Lacq	FR	O	27	0.06	Onshore	Depleted oil/gas field

Legend: P = Planned, O = Operational.

Table 2: CO_2 Pipeline Projects in Europe (source: IEA, 2014)

There is likely ample CO_2 storage potential in Europe, mostly offshore, such as the North Sea Basin. Deep saline aquifers offshore provide the largest capacity and scalability in which Europe is rich in.

[222] Serpa et al., 2011

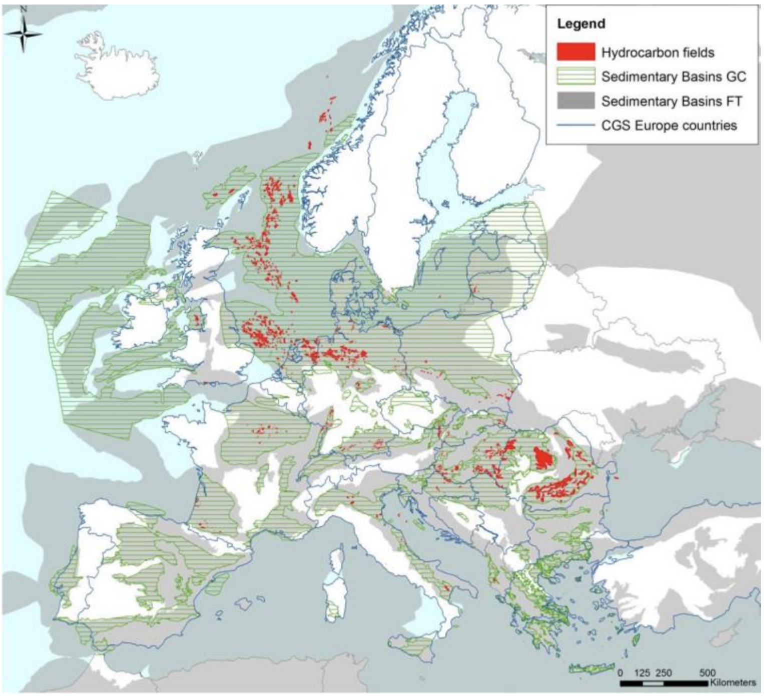

Figure 49: Storage options, potentials and capacities in Europe (Source: Rütters, H. and the CGS Europe partners, 2013)

The geological storage potential for CO_2 in Europe is estimated at around 134 $GtCO_2$ (taking into account storage restrictions in some Member States).[223] Emissions of all EU energy intensive industries are between 600-700 Mt per year, whichh implies over 190 years of storage capacity at current emission rates for energy intensive industries. However, given the multitude of other mitigation options in industry (e.g. biomass, electrification, green hydrogen and utilisation of CO_2) the actual annual CO_2 storage needs for industry will be much lower.

It is noteworthy that EU emission clusters and storage locations are to be found in close proximity which permits greater ease of access for EU energy intensive industries to CO_2 storage.

[223] IOGP, 2019

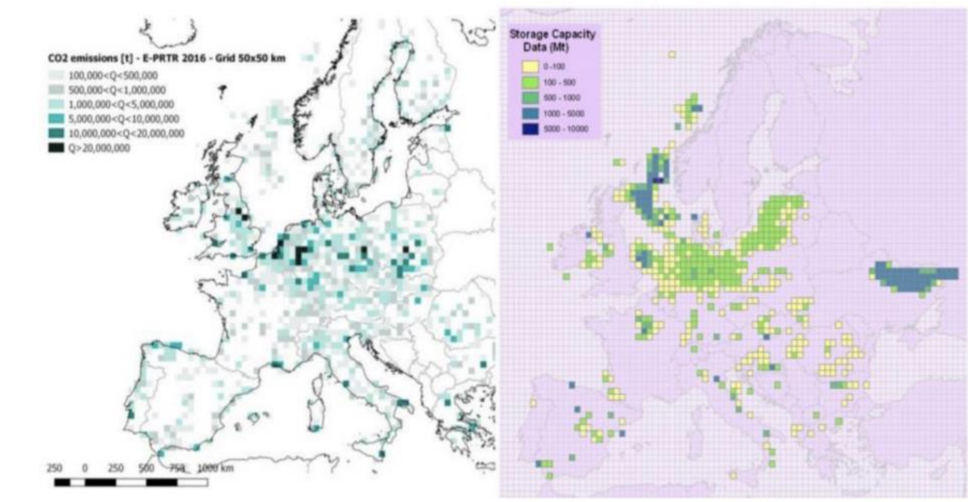

Figure 50: Comparison of CO2 emission clusters and CO2 storage capacity in Europe (Source: IOGP, 2019)

Ongoing storage projects in Europe (discussed in detail in section 10) include the Porthos project in the Netherlands, the Northern Lights project in Norway and possibly one in Belgium called Antwerp@C. The Porthos project,[224] seeks to be able to store 2-5 million tonnes of CO_2 per year in depleted offshore gas fields beneath the North Sea by the end of 2023. The Antwerp@C project led by eight petrochemical companies in the Port of Antwerp aim to build a CCUS project at the Port of Antwerp (if be technically and economically feasible) by 2030. The Northern Lights project is a Norwegian initiative that includes capture of CO_2 from industrial capture sources in the Oslo-fjord region, shipping of liquid CO_2 to an onshore terminal on the Norwegian west coast, and eventual transportation by pipeline to an offshore storage location subsea in the North Sea. It hopes to accommodate large CO_2 volumes from across Europe.

There are different estimations of costs. ZEP platform estimates that in a mature CCS industry, the technical cost of storing CO_2 in offshore storage reservoirs is expected to lie in the range EUR 2–20 /t while the addition of transport and compression bring the cost to between EUR 12–30 /t.[225] SINTEF's CCS calculations assume transport and storage cost at USD 25/t CO_2.[226] A UK study of five offshore sites [Pale Blue Dot, 2016] estimated (technical) unit costs for offshore transport and storage at EUR 13–20 /t while a more recent Dutch EBN-Gasunie, 2017 roadmap estimated technical cost of storage in the range of EUR 2-10/t and cost of transport by pipeline in the range of EUR 1-2/t (with distances generally shorter than 180 km) (compression adds about EUR 9/t).

CO_2 storage costs depend on location and are highest in offshore deep saline aquifers where the storage capacity is far greater than onshore basins or offshore depleted oil and gas fields. This means that deep saline formations therefore have a better scaling-up and cost reduction potential. Storage costs are in any case much lower than capture costs.

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[224] Port of Rotterdam, 2019
[225] Zero Emissions Platform, 2019
[226] Sintef, 2019

Below is an overview of storage costs in Europe by type of formation.

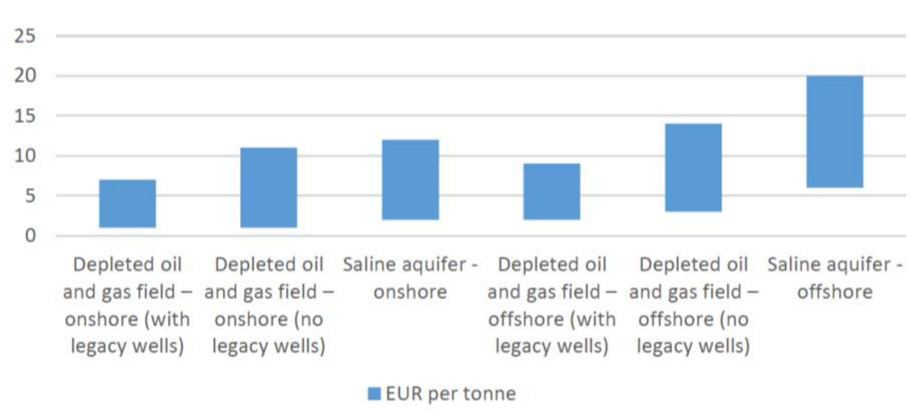

Figure 51: Storage costs in Europe per geological formation type (Source: ZEP, 2019)

9.1.8 Overview of technology options for low-CO_2 chemicals production

Through this chapter, technologies for deep CO_2 reductions in (basic) chemicals production, with focus on high emission intensive HVC production, have been assessed from multiple angles:

- Breakthrough process efficiency gains, mostly via innovative catalytic processes
- Innovative electrification technologies for processes
- Bringing polymers waste back into the chemicals value chain as a replacement of fossil fuel-based feedstock
- The use of bio-based feedstock as starting point for current HVC production and/or for other bio-based polymers
- The utilisation of CO_2 emissions together with low-CO_2 hydrogen as a starting point for the HVC value chain. This includes the options and challlenges to capture CO_2 from incumbent processes
- Concepts that allow deep emissions reductions in heat/steam production for chemical processes through electrification, low-CO_2 fuels, system integration at industrial cluster level (applying economies of scale for carbon capture and steam production) and the possible enhanced symbiosis between industrial and power production (e.g. power storage and demand repsonse).

To be succesful in transforming the basic chemicals value chain towards climate neutrality, these different angles or pathways must be compatible. It is likely this is the case. In particular, the emergence of new platform molecules such as methanol and (to a lesser extent) ethanol which can be derived from plastic waste (gasification), biobased, via CO_2 utilisation and via classical routes with carbon capture demonstrate the concept of consistency along the different approaches.

Secondly from a perspective of timing a smart combination of options would allow the chemicals industry to gradually move from the current modus operandi to one where carbon is more circular and the remaining GHG emissions are very small. The logic here is to use the existing assets in a smart manner while building up the capacity towards a low-CO_2 production system. This in practice implies deploying carbon capture technologies (and provide infrastructure) on the high concentration sources as soon as possible. But at the same time invest, to in new technologies that will become essential over time, such as (chemical) recycling of plastics (driven by both waste reduction and climate protection). Similarly, new and material efficient bio-based chemicals production has to be demonstrated either to feed the classic HVC value chain and/or towards the development of bio-based HVC- and polymer-equivalents. Preparing the infrastructure for CO_2 capture and transport and for additional hydrogen together with demonstration of promising CCU processes (e.g. methanol to olefins) sets the stage for full scale implementation of CO_2 utilisation after 2030. It is very likely that electricity and its reliable and competitively priced supply will become much more important for chemicals production. This can be either through hydrogen production, electrification of heat and carbon capture or via the promising routes that electrify large process installations (e.g. highly efficient electrical steam crackers).

It is clear that the transition of the chemicals industry will require the development of new supply chains which will replace most of the current feedstock. Therefore, it will be essential to develop the necessary logistics e.g. shipping, (inter)national pipelines (hydrogen and CO_2), increased capacity of international power transmission lines to large scale renewables and reliable biomass and plastic waste supply chains.

The flowchart below seeks to give a summary of the technology options discussed in this chapter and how they fit within the starting points of the high value chemicals value chain.

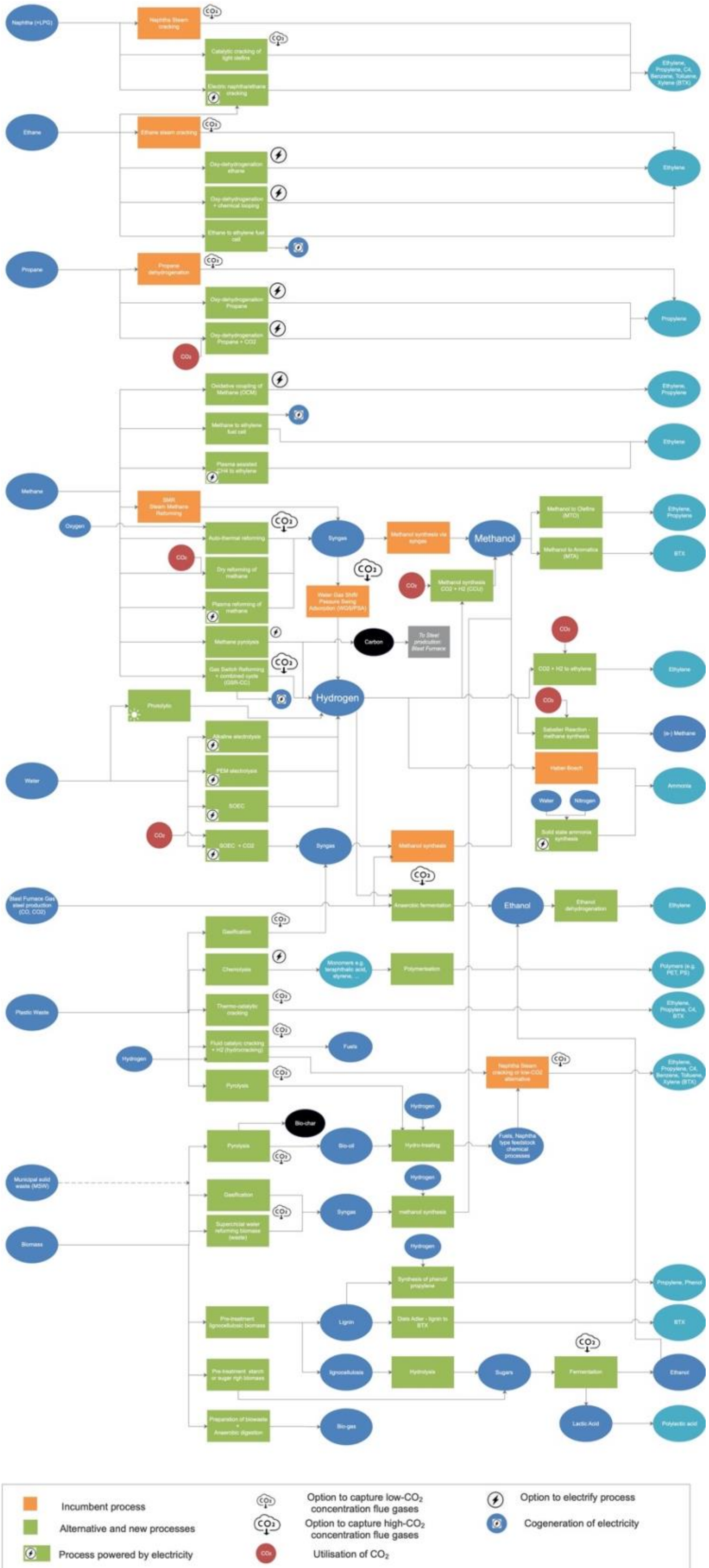

Figure 52: Overview of existing and new low-CO_2 processes for production of high value chemicals

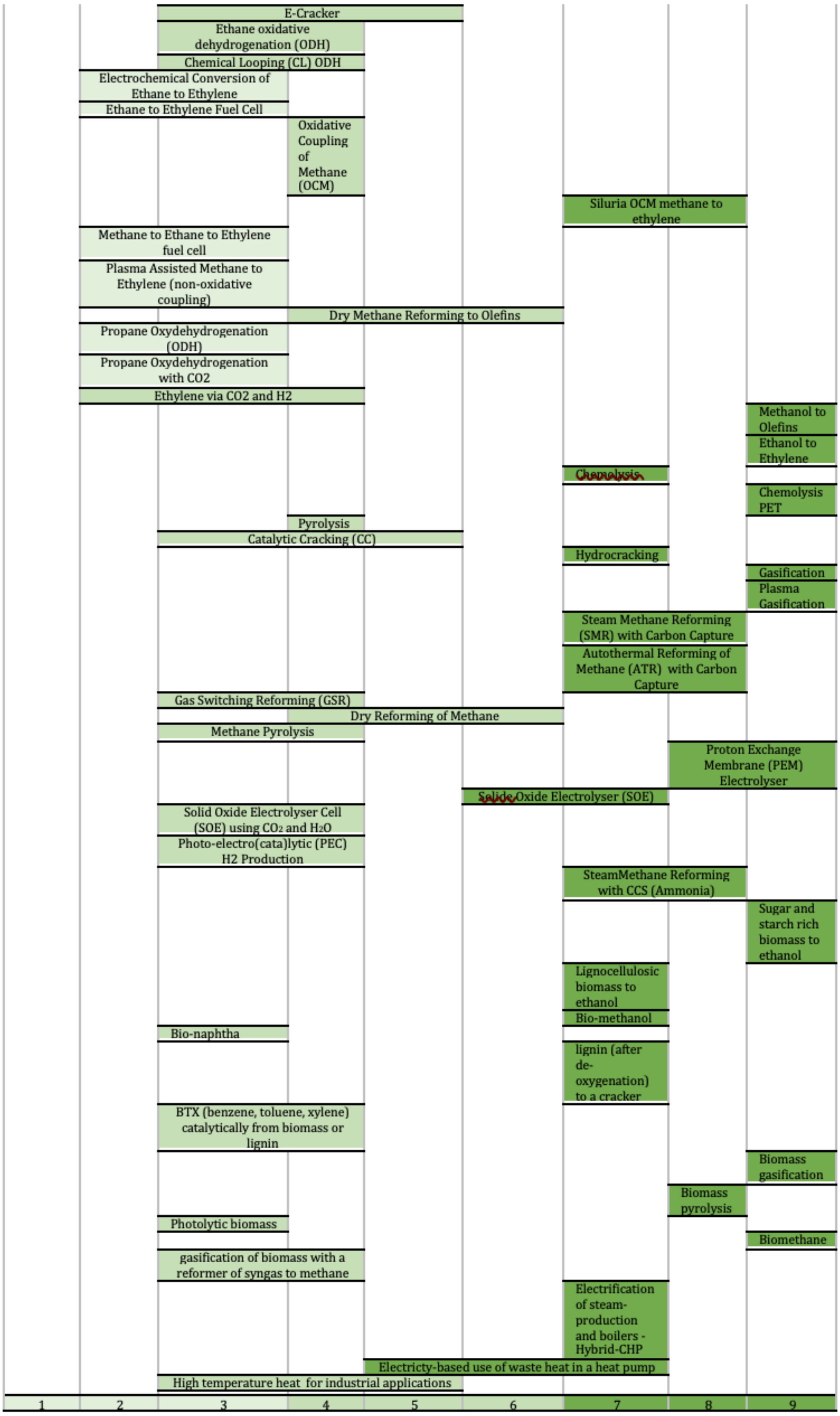

Figure 53: Overview of technologies and their Technology Readiness Levels (TRLs)

9.2 Technological options for deep emission reductions in the refining industry

9.2.1 Introduction

The technologies and techniques for the refining industry presented below are derived from two reports by Concawe on mitigation pathways for g reenhouse gas emisssions in refining and on the future of liquid fuels in the EU.

The next section looks at the options for reducing emissions from the refining of crude oil and where possible the implications for refining in Flanders.

This is followed by a brief presentation on alternative fuels to fossil fuels such as biofuels and e-fuels. Most of these have already been presented before when considering alternative feedstock and energy for the chemicals industry. Here the technological details of the options will not be discussed in detail given that these (e.g. hydrogen, biomass, e-fuels, carbon capture) have been presented in the previous chapter covering chemicals.

9.2.2 Technologies to reduce emissions in refining of crude oil[227]

The main technological options to reduce emissions in refining of crude oil include:

- Enhancing the efficiency of processes and materials recovery
- Electricifation of heating/boilers and use of low-CO_2 hydrogen
- Carbon capture and storage or utilisation

9.2.2.1 Further improving Energy Efficiency

In general, there is an important potential for emission reductions linked to energy efficiency improvements, but that does not imply these all are still applicable to refineries in Flanders with the same mitigation potential. For instance, in Flanders some newer efficiency measures might already have been implemented. The activities related to efficiency improvements are:

- Continuous improvement of processes
- Large new investments in efficiency improvements
- Improved inter-unit heat integration
- Improved energy management systems
- Lowe grade heat recovery systems
- Improved recovery of hydrogen, LPG (and HVCs) from fuel gas

According to Concawe these improvements together could lead to CO_2 reductions of 20% by 2050[228].

Continuous improvement of processes in refining would happen through implementation of a combination of measures and projects involving some capital expenditure. Examples include fouling mitigation, catalyst

[227] This section is based on Concawe, 2018a; Concawe, 2018b; Concawe, 2018c; Fuels Europe, 2018; Clingendaelenergy
[228] Compared to 2030 baseline

improvements and hardware improvements such as new motors, heat-exchangers, etc. TRL is estimated at 6-8.

When it comes to major capital projects these reflect larger efficiency improvements reflecting changes to the technical configuration of individual refineries (e.g. extensive revamps of existing facilities, new process plants). This includes replacing older installations with Best Available Technologies (BAT). The TRL range is broad (3-8) given the diversity of possible applications.

If not already optimalised inter-unit heat integration (TRL 6-8) would also lead to overall efficiency gains and hence reduction in emissions. This also relates to enhanced Energy Management Systems (TRL 6-8) that combine combine equipment (e.g. energy measurement and control systems) with strategic planning, organisation and culture.

Finally, an important challenge will be the increased recovery and upgrading of refinery low-grade heat (via e.g. chemical heatpumps) for electricity production, internal use (e.g. supporting carbon capture) and export to other industries and sectors. TRL is estimated at 3-6.

Finally, the improved recovery of valuable gas streams from fuel gas, such as hydrogen, LPG and HVCs would impact the overall energy use of refineries, also these with integrated HVC production. Such project has already been implemented by a refinery in Flanders. Overall TRL is estimated at 4-9 dependig on the type of technolgy used.

9.2.2.2 Electrification of processes, heat and hydrogen

Electrification of some of the refining processes is an important option for greenhouse gas mitigation in refining. Overall, Concawe estimates that 25% emission reductions are possible by 2050[229] (vs ref. 2030) due this approach, assuming the efficiency measure mentioned before are implemented.

Electrification in refining includes the following elements:

- Higher level of electrification in machinery and general operations (TRL 8)
- The use of electric heaters and boilers by substitution of fired heater/boilers by electric heaters (TRL 4-8)
- Production of hydrogen with electricity (e.g. replacing steam methane reforming) (TRL 8-9)

While the emissions of combustion processes in refining is high (e.g. furnaces) and it is in theory technically possible to replace most with electric furnaces, there is a major techno-economic barrier in their broad deployment in refining. The reason is that the most important fuel in refining is auto-generated refining gas from the distillation processes. This gas is in essence unavoidable. Not using it by replacing its use with electricity would not make economic sense, but also still leaves the refining gas in place likely for combustion elsewhere. So high electrification would also not further mitigate greenhouse gas emissions.

[229] Compared to 2030 baseline.

9.2.2.3 The use of Carbon Capture and Storage and/or Utilisation

As seen above, energy efficiency and electrification will bring about important greenhouse gas emissions reductions but still leave more than half of the emissions in place. It is hence very likely that carbon capture will need to play an important role for deep greenhouse gas emissions in refining.

In general, at a complex refinery three categories of CO_2 sources for carbon capture can be identified. First, and least costly for capture, are the high pressure or high concentration sources. These sources can mainly be found at hydrogen production units and will make up 5-20% of a refinery's emissions. The second category is made up by a number of large flue gas sources at a refinery. This category typically will form 30-50% of the refinery CO_2 emissions. Emission sources in this category are for example large stacks from furnaces and gas turbines, or the off gas from the refinery's utilities plant. Due to their large size, these offer the lowest costs of post-combustion capture for flue gas at refineries. The third category, about 50% of total refinery CO_2 emissions, is a large number of small, low concentration sources scattered around the site. The costs of capture from these small sources will be very high. The geographic lay out of a complex refinery is such, that ducting of small sources to one capture point will bring along high additional costs.[230]

For combustion processes post-combustion carbon capture (e.g with use of amines) is chosen mostly in literature. But for fluid catalytic cracking and regeneration of the catalyst oxy-fuel (pre-combusion) technology can be applied. Also, for steam methane reforming for hydrogen production the known pre-combustion technologies can be applied.

Concawe estimated that this can reduce emissions by another 25% (by 2050 ref. 2030) after the mitigation by efficiency measures and electrification have been implemented. Current TRL for carbon capture in refining is set at 6-7. This 25% of further reduction from emissions to be captured (or around 50% avoided emissions) seems a low estimate. A comprehensive study by SINTEF[231] on carbon capture in refining assumed the technological possibilty 90% of emissions and 90% capture rate bringing possible capturing of remaing emissions to 80%.[232]

Capturing CO_2 in integrated refineries will be complex due to the large amount of diverse point sources. Hence integration of stacks should be considered, but this comes with complex engineering and additional costs. Furthermore, utlities will be needed to provide heat and power to carbon capture processes, adding to the costs. SINTEF estimated the cost of avoided CO_2 via capturing for refineries at 128.5-187 EUR/t CO_2[233]. An

[230] Van Straelen et al., 2009
[231] Roussanaly et al., 2017
[232] The SINTEF study (ibid) ends up with 60% capture rate by adding a CHP plant as utility for carbon capture for which the emissions were not captured.
[233] Cost for refining are notably higher due to the complexity of capture integration in refineries with large amounts of point sources. In these costs the cost for additional utilities are included. USD to EUR at 2017 rate. Roussanaly et al., (SINTEF), 2017

important part of this cost is due to connecting infrastructure and utilities for capture.

9.2.2.4 Impact on emissions, energy use and capex

Concawe estimated the maximum mitigation potential to be around 70% for refining by 2050 (ref. 2030 baseline). However, as mentioned above, the rate of carbon capture can be higher, bringing the mitigation potential beyond 80%.

The capex required to implement these technologies has been preliminary estimated at minimum EUR 45,000 Mn for the whole EU refining system. This estimated cost only refers to the generic cost of the different technologies and opportunities identified. The actual cost of implementation would be determined by the specific conditions of each individual asset. With Flanders at around 5.5% of EU refining capacity the proportional investment cost would be around EUR 2.5 Bn minimum.[234]

The scenarios analysed will require additional energy, alternative feedstocks and infrastructure needs. As a preliminary assessment focused on some illustrative pathways, the results of the ongoing Concawe's modelling work show the following potential needs of additional energy by 2050 of Up to 85 TWh/y. Assuming again Flemisch refining capacity to be proportion to this additional demand for the EU, this would result in 4.67 TWh additional energy demand for low-CO_2 refining in Flanders.

9.2.3 Alternative fuels

Next to reducing the emissions in the refining process, the refining industry can also consider changing its business model with a move away from crude oil as input towards the development of e-fuels and/or biofuels. While this falls outside of the scope of this report it is worth mentioning briefly the types of fuels that can be thought of in this context.

E-fuels/gas:

- e-methanol: produced via CO_2 and hydrogen
- e-DME (dimethylether), e-OME (oxymethylene ether): produced via CO_2 and hydrogen
- e-gasoline, e-diesel, e-jetfuel: via e-methanol synthesis and/or Fischer-Tropsch process (using CO_2 and hydrogen)
- e-methane: via the Sabatier process
- e-ammonia: produced with electrolysis-based hydrogen

Biofuels:

- Lipid biofuels: production of biodiesel and jet from oil rich biomass (e.g. rapeseed, palm, soy, animal fat) and at a later stage maybe from algae
- Lignocellulosis to syngas to methanol
- Lignocellulosis via fermentation to ethanol

[234] EU refining capacity is 14 million barrels a day (ref. European Commission, 2020a) Belgium/Flanders 0.776 million barrels a day or 5.5% of EU capacity, (ref. Statista, 2019)

The transition to use of e-fuels or biofuels will be important in particular for sectors where electrificiation or to lesser extent the use of hydrogen will be difficult if not impossible (e.g aviation, shipping).

Existing refinig capacity is fine-tuned towards (even specific types) of crude oil, so changing business models towards e- and/or biofuels will require a major overhaul of refinining infrastructure. At the early stage integration via e.g. bio- or e-fuel drop ins into existing refining products is definitely possible (and happening already), but at higher volumes this will become more challenging.

The EU demand for e-fuels production can range from 50 Mtoe/a in 2030 of to 100 Mtoe/a by 2040. These could be covered from CO_2 generated from large point sources like industry or power sector. However, some studies estimate the demand to be around 400 Mtoe/a of e-fuels by 2050 (high FVV, dena and Dechema scenarios) which may prove problematic, especially beyond 2050 and necessitate the implementation of direct air capture technologies. From a geographical point of view, e-fuels production sites would be located close to sources of low-carbon power and industrial CO_2 as well as other necessary infrastructure and utilities.

9.3 Technological options for deep emission reductions in the steel industry

9.3.1 Introduction

There exist three main routes for iron and steel production. The Blast-Furnace (BF) and Blast Oxygen Furnace (BOF) route in whichh cokes and coal are used to reduce molten iron ore. The hot iron (pig iron) next sees excess carbon removed via oxygenation in the blast oxygen furnace. The result is steel with a low carbon content. The second route converts iron ore directly (e.g. via natural gas) to (sponge) iron without melting. The sponge iron is converted to steel via an electric arc furnace (EAF). The third route uses steel scrap which is converted to steel in an electric arc furnace.

In flanders steel production foremost happens via BF-BOF, with smaller amount produced via EAF. Steel production via BF-BOF emits 1.7-1.8 t CO_2 emissions per tonne steel. Around 550 kg coal is used per tonne steel.

For deep greenhouse gas reductions in steel production three pathways are considered by the EU steel industry:[235]

- The use of renewable electricity in basic steelmaking, including the use of hydrogen to replace carbon as reducing agent[236]
- The use of CO_2 or CO from steel production as a raw material for e.g. production of basic chemicals
- New processes and process integration in steelmaking with reduced use of carbon (incl. CCS and use of biomass and plastic waste in steelmaking)

Some of the technologies under these pathways can be combined to achieve deep greenhouse gas reductions in integrated steel mills.

In the next sections the pathways will be briefly presented. This is followed by discussing the specific options for integrated low-CO_2 BF-BOF steelmaking in Flanders.

9.3.1.1 Electricity-based steelmaking and use of hydrogen

Use of hydrogen to produce iron
Hydrogen (pure, or present in syngas) or methane can also be injected in a traditional blast furnace as reducing agents even though it is not possible to completely substitute coke with other reducing agents. A partial decrease in GHG emission from the BF is possible: a reduction of about 20% in emissions from the blast furnace is obtained by injecting 27kg of hydrogen per tonne of pig metal produced.

An almost complete substitution of coal/cokes or natural gas with hydrogen is however possible in the DRI process, with 1 kg of hydrogen is estimated to produce around 15kg of solid metallic iron.[237]

[235] Ghenda, 2018
[236] Low Carbon Future, n.d.,
[237] Vogl et al. 2018

Direct reduction of iron ore with the use of hydrogen is and endothermic process, whereas reduction with CO (produced by partial oxidation of coke coal) is exothermic. This implies heat must be continuously supplied from an external source during the ore reduction process if hydrogen is used as a reducing agent. The process can be virtually CO_2-free given that the hydrogen-based reduction process runs mostly on electricity which can be renewable. Moreover, it can allow for balancing renewable power loads given flexible production (Vogl et al. 2018). Currently, this pathway remains between 20-30% more expensive than current integrated steel plants, but lower electricity prices, higher CO_2 prices and increased scrap use could lower the pathway costs.[238]

As elaborated in the Chapter 9.1 on chemicals technologies, hydrogen can be produced via water electrolysis, via steam methane reforming and carbon capture and storage or utilisation or via methane pyrolysis. A side product of electrolytic hydrogen production is the production of oxygen during water electrolysis. This by-product can be directly used inside the steel mill e.g. as oxidizer for internal combustion / heating processes.

Electrified primary steelmaking
In theory it is possible to have a fully electricity-based, CO_2-free steelmaking process using an electrolytic process (flexible enough to be supplied by renewable energies), which will transform iron oxide, into steel with a significant reduction of energy use. The electrowinning of iron is based on the reaction of decomposition of hematite into iron metal and oxygen by supplying energy as electricity. This reaction is carried out in an aqueous solution composed of sodium hydroxide and water. Contrary to conventional electrowinning, iron is not reduced as an ion but as a solid. This particular chemical route supposes a specific electrowinning technology, which departs significantly from conventional treatment of Ni, Cu or Zn, cf.[239]

An alternative high temperature route for electricity-based iron production is molten oxide electrolysis (MOE) and combines transformative materials engineering and novel systems engineering with elements from industrial aluminum production, traditional blast furnaces, and arc furnaces to produce steel via electricity with low greenhouse gas emissions.[240]

Finally, further electrification of steel production can be achieved by gradually replacing blast oxygen furnaces (BOF) with electric arc furnaces (EAF), but this is only possible with availability of additional scrap steel. Currently most steel is already recycled.

9.3.1.2 New processes and process integration in steelmaking with reduced use of carbon and with the use of carbon capture and storage

This approach seeks to reduce the emissions from in particular BF-BOF via a redesign of current blast furnaces to improve efficiency, via reduction of coal use through other carbon-based feedstock and ultimately via capturing

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[238] Lechtenbohmer et al., 2018
[239] European Commission, 2016
[240] EngineX, n.d.,

an storing the remainig CO_2 emissions. This approach has the advantage that, in most cases, the existing BF-BOF assets can be kept operational. [241]

Examples of this approach are:

- New blast furnace design (direct melting) with higher efficiency and with almost capture ready CO_2 emissions at the stack.
- The use of biomass, plastics waste and CO_2 in the blast furnace. This route also allows steel production to play a role in the circular economy
- Using carbon monoxide in the blast furnace gas to enhance hydrogen production and achieving high concentration CO_2 emissions for capture

9.3.1.3 Carbon Capture and Utilisation

Blast furnace gas (but also cokes oven gas and BOF convertor gas) is an interesting as starting point for carbon capture and utilisation. This is because blast furnace gas contains a fixed amount of carbon monoxide (50/50: CO/CO_2) which is energetically much moreeasy to process towards high value chemicals vis-à-vis CO_2. Utilisation of blast furnace gas towards chemicals will however still require a large amount of additional hydrogen. Additional hydrogen needed for the production of hydrocarbons can come from other low-CO_2 pathways such as electrolysis, steam methane reforming with CCS, methane pyrolyis and the above-mentioned sorption enhanced water gas shift.[242]

Products that are currently considered from blast furnace gas derived CO and/or CO_2 include:

- Methanol: via methanol synthesis from low-CO_2 hydrogen
- Ethanol: via fermentation of blast furnace gas with addition of hydrogen to increase yield
- Polyurethane: via CO/CO_2 added in polyols production
- Urea or melamine: by extraction of nitrogen from flue gases and addition of hydrogen to ammonia and next addition of CO_2 for urea and melamine.[243]
- Proteins: Advanced use of CO_2 for production of proteins to be used in animal feed or as meat replacement.[244]

[241] Low Carbon Future, n.d.,
[242] Ibid.,
[243] Rijksdienst voor Ondernemend Nederland, 2016
[244] Solarfoods, n.d.,

	Name	Description	TRL	Emissions & Energy Use	Economic Data	Pilot
Hydrogen & Electricity Based	Hybrit	HYBRIT – short for Hydrogen Breakthrough Ironmaking Technology – is a joint venture between SSAB, LKAB and Vattenfall, aiming to replace coal with hydrogen in the steelmaking process. HYBRIT is a ground-breaking effort to reduce CO2 emissions and de-carbonise the steel industry.	4-5	**CO2 emissions**: 95% less CO2 emissions or around 25kgCO2/t crude steel. **Energy use**: Bio: 380kWh, Electricity: 816kWh, Coal: 42 kWh. 75% (based on the Swedish energy mix) lower primary energy demand from approx. 5200kWh to 600kWh per ton of steel but higher electricity demand, from approx. 200 kWh to 3500 kWh	**CAPEX**: The three actors have, together with the Swedish Energy Agency (which will take about one third of the cost), committed to invest €135,5 Mn in the pilot plant. **OPEX**: Depends on electricity price. For the price of 20 EUR/MWh, OPEX are equal, for 40€ OPEX is +24%, for 60€ it would be +47%.	Pilot between 2018-24, demonstration between 2025-2035.
	Salcos	SALCOS is based on the industrial direct reduction process using, in addition to natural gas, flexible amounts of hydrogen, produced by renewable energy to significantly reduce the CO2 emissions short term for the steel production, because of the used industrial processes. Salzgitter Flachstahl GmbH (SZFG) has awarded the contract to build a 2.2 MW Proton Exchange Membrane (PEM) electrolysis plant to Siemens Gas and Power, marking an important step towards hydrogen-based steelmaking.	7-9	**CO2 emissions**: -26-95% (-26% CO2 compared to current BF-BOF production; -82% CO2 if operated with 55% H2; -95% CO2 if operated with 100% H2). **Energy use**: For a final total reconfiguration of the existing plants and the use of a mix of 55% hydrogen produced by electrolysis and 45% natural gas, the estimated electrical power consumption is 12.4TWh/y (8.8TWh/y used for electrolysis), with an additional requirement of 23PJ/y of natural gas.	**CAPEX**: Capex of the integrated project is estimated to be around €1.3 Bn for the realisation of stage 2 (one DRP, one EAF and necessary electrolyzer capacity). PEM electrolyser costs – including the construction of the wind turbines and the hydrogen plant and connecting these to the existing supply networks – around 50 million euro ($50m).	
	GrinHy	GrInHy, the world's most powerful Steam Electrolyser (StE) is being constructed for the energy efficient production of hydrogen. The GrInHy-project operated high temperature electrolyzer (HTE) enables the production of hydrogen with the highest electrical efficiency by using waste heat. GrInHy2.0 marks the first implementation of a HTE with an electrical power input of 720 kilowatt in an industrial environment. By the end of 2022 it is expected to have been producing a total of around 100 tonnes of high-purity (99.98 %) hydrogen used in steelworks as a replacement for hydrogen produced from natural gas. GrInHy2.0 is the successor of the GrInHy project (03/2016 - 02/2019).	5-6	**Energy use**: Electrical power input of 720 kilowatt	**CAPEX**: The GrInHy2.0 project (Green Industrial Hydrogen via steam electrolysis) has an overall budget of € 5.5 million.	
	H2Futures	H2FUTURE is a European flagship project for the generation of green hydrogen from electricity from renewable energy sources. Under the coordination of the utility VERBUND, the steel manufacturer Voestalpine and Siemens, a proton exchange membrane (PEM) electrolyser manufacturer, a large-scale 6 MW PEM electrolysis system will be installed and operated at the Voestalpine Linz steel plant in Austria. The nominal production capacity of this plant is about 1,200 m3 hydrogen per hour.	6-7	**CO2 emissions**: <20% kg/t crude steel (depending on share of CO2 for energy). 50g/kWh CO2. **Energy use**: 430kWh/t	**CAPEX**: 2017-2012: 17mn EUR, 2021-2030: 30mn EUR. Project budget EUR 18 m, Total EU funding EUR 12 m (70% funding rate). Project duration 4.5 years (2017-2021) **OPEX**: Industrial Upscaling EUR 1bn between 2030-2035, investments between 2035-2050: 6-7bn Eur	Project launched in 2017 (duration of 4.5yrs). H2 production of 1,200 m3/h at Voestalpine's Linz site (full scale demonstration of H2 production and grid balancing).
	SuSteel	The SUSTEEL technology is based on the idea of hydrogen-based DRI-EAF steelmaking, yet, combines both processes, DRI production and EAF steelmaking, into one single process. (Hydrogen Plasma Smelting Reduction: HPSR process) and uses the H2 Future hydrogen technology.	4-5	**Energy use**: When hydrogen is produced from electrolysis and renewable electricity, the whole process is estimated to need between 3.5-5.4MWh per tonne of steel; electrolysis will amount to about 2.6-2.7MWh (about 50-77% of the total energy consumption) per tonne of steel.	**CAPEX**: 2,6 M€; Funding rate: 60 %	Upscaling from an existing laboratory reactor from 100g to 20 kg batch operation at voestalpine Donawitz site

	Siderwin	SIDERWIN (previously ULCOWIN) is based on CO2-free steelmaking through electrolysis, transforming iron oxide (e.g. hematite) into a steel plate (at the cathode) and oxygen (anode).	6	**CO2 emissions**: 87% less. (Reduction by 87% of direct CO2 emissions) **Energy use**: 3.6 MWh.t-1 Fe or 13 GJ.t-1 Fe. Reduction by 31% of direct energy use.	**CAPEX**: The project has received €6,8 Mn (includes 2.2 M€ for pilot) through SPIRE. It is a 5 years project (2017-2022).	
Process Integration and CCS	Hisarna	Hisarna is a new type of furnace in which iron ore is directly injected and liquefied in a high-temperature cyclone so that it drips to the bottom of the reactor where powder coal is injected. The two react into liquid iron. One main further advantage is that the Hisarna process leads to waste gases with high CO2 concentration and can hence be relatively easy combined with CO2 capturing (and storage).	7	**CO2 emissions**: Min 20% emission mitigation; 35% (with high scrap use); 80% (with CCS). **Energy use**: 80%. (At least 20% lower energy demand than BF-BOF).	The pilot project has received funding under Horizon2020 (SILC-II). To date, €75 has been invested into the project, of which 60% has been funded by the partner companies and 40% from the EU, the Dutch Economics Ministry and the European Research Fund for Coal and Steel. Expected project cost €300Mn.	Pilot plant at IJmuiden since 2011 producing 60,000 thm/year jointly developed by Tata Steel and Rio Tinto.
	Stepwise	The stepwise project seeks to capture blast furnace gases and processes them through an advanced water-gas shift technology (which creates higher concentration CO2 waste gases). The waste gases are cleaned through SEWGS (Sorption Enhanced Water-Gas Shift). Three key components in the STEPWISE technology chain are coupled together: an industrial syngas source, syngas pre-processing with advanced water-gas shift, and CO and H2S clean-up with simultaneous CO2 removal in the SEWGS reactor. Great progress has been made on the required materials.	3-4	**CO2 emissions**: -85% (due to higher carbon capture rate). **Energy use**: -60% (60% lower SPECCA - Specific Energy Consumption for CO2 Avoided).	**CAPEX**: Received funding under EU Horizon 2020's project (LCE-15-2014). Expected project cost is €13M.	**Pilot**: Pilot plant at Swerea/Mefos in Sweden demonstrated at a CO2 capture rate of 14t/day.
	IGAR	The IGAR process aims for process-integrated CO2-capture through top-gas recycling in a blast furnace by means of a plasma torch and reactor to heat and reform gases, enabling less coke/coal consumption. This can include reforming of methane and CO2 but also plastic waste.	5-8	**CO2 emissions**: -25%. (-60% with CCS/U) (reducing CO2j production by 90 to 180 kg per ton of steel). Potential CO2 savings of 0.1-0.3tCO2/t crude steel. For one typical plant 500 ktCO2eq/a. Total EU scope estimated is 10 MtCO2eq/a. **Energy use**: 15% energy savings.	**CAPEX**: Estimated cost: 21,0M€. Funding received: 9,2 M€.	**Pilot**: ArcelorMittal- First demo in Dunkirk. Market entry by 2025.
	Torero	Torero is a torrefaction technology that transforms wood waste into biocoal which the powdered coal in the blast furnace. This process will be linked to the Steelanol process where carbon monoxide is transformed into ethanol via anaerobic fermentation. This technology therefore provides the unique opportunity to recycle the carbon from industrial exhaust rich gases that would otherwise be emitted into the atmosphere. Every steel mill that implements this concept will be able to produce at least 80 million litres of bioethanol per year.	5-8	**CO2 emissions**: -400,000 tCO2 together with Steelanol.	**CAPEX**: Total cost: €30m. EU contribution: €11,472,916. **OPEX**: 1/3 lower than current first generation production based cellulosic bio-ethanol solution.	Developed by Torr-Coal and will be implemented at the ArcelorMittal steel plant in Ghent at the end of 2020 with Steelanol.
CCU	Carbon2 Chem	Carbon2Chem is based on the utilisation of industrial waste gases (top gases from steel production) for chemicals production such as methanol. Under Thyssenkrupp's project Carbon2Chem Thyssenkrupp Uhde Chlorine Engineers will install a 2 MW electrolysis plant showcasing the technology and the integration of renewable energy into an existing steel plant.	7-8	**CO2 emissions**: CO2-free steel. Utilization of approx. 60% of the Top Gases. **Energy use**: Will use renewable energy.	**CAPEX**: Received over €60Mn from the German Federal Ministry of Education and Research. Partners involved intend to invest >€100Mn by 2025 and have earmarked >€1Bn for commercial realisation.	**Pilot**: Start: 2023. Demonstration at an estimated cost of € 500 million.
	Steelanol	Steelanol uses blast furnace gas to make liquid hydrocarbons (such as ethanol), via a novel gas-fermentation technology. The steel industry exhaust gases present a high concentration of CO (24%-56%). The steelanol technology is expected to uptake around 90% of the CO to produce around 50 kg of ethanol per tonne of steel produced. If all steel mill gasses of EU 28 conventional steel plants (BF-BOF route) are converted into ethanol the yearly production potential of approximately.	4-6	**CO2 emissions**: -65% (if fully deployed through EU bioethanol production of 2.5 Mn tons). CO2 emissions from Steelanol-biofuels are 50-70% lower than petroleum-based fuels, and around -35% compared to when steel plant off-gases are converted into electricity.	**CAPEX**: The project has received €10.2Mn funding from the European Union's Horizon 2020 research and innovation program. Expected project cost is €150Mn (a project with Lanzatech). **OPEX**: Electriicty to compress the gas + avoided energy value of CO because you don't burn it anymore.	Developed by LanzaTech, implemented by ArcelorMittal in Ghent with the goal to produce around 80 million litres of bioethanol yearly. First

		14,5 million t/y of EtOH will reduce CO2 emissions by 33,3 million t/y.		**Energy use:** Low additional energy demand (Improved overall efficiency for steel plant off-gases.	On large scale of 1mt/yr, it would be competitive to current naphtha-based business.	production is expected by mid-2020.
	FreSme	The FReSMe technology captures CO2 from steel production for production of methanol fuel to be utilised in the chemicals and ship transportation sector. Project linked to the STEPWISE and the MefCO2 technologies. The project combines three existing technologies: • sorption-enhanced water–gas shift (SEWGS) technology for CO2 enrichment of the blast furnace gas and its subsequent decarbonisation; • state-of-the-art and commercially available hydrolysers to produce hydrogen; methanol production from carbon dioxide and hydrogen.	6	**CO2 emissions**: -1050 kgCO2/tMeOH. **Energy use**: Natural gas: 3.61 GJ/t MeOH, electricity: 2.19 GJ/t MeOH (13 GJ/tMeOH for conventional methanol production), electricity for the electrolyzer: 36.83 GJ/t MeOH. There is a small amount of natural gas, it is required for the distillation process.	**CAPEX**: Total cost: €11,406,725, EU contribution: €11,406,725. This project has received funding from the European Union's Horizon 2020 research and innovation programme.	Pilots: 1) At Swerea MEFOS facility in Luleå, Sweden. (Capacity: 1t/day). 2) CRI's CO2-to-methanol demonstration plant, Svartsengi, Iceland (Capacity 12t/day).
	Valorco	The VALORCO project coordinated by ArcelorMittal and funded by ADEME aims at reducing and valorizing CO2 emissions from steel industry blast furnace gases by means of amine scrubbing technologies (DMX).	3-5	**CO2 emissions:** CO2 capture rate: >99.5 % (0.5 tCO2 captured/hour). Possible to produce CO2 at around 40 €/t by using the DMXTM process.	**CAPEX:** Estimated costs: 19,2 M€. EU funding: 14,7 M€ **OPEX:** CO2 produced at 6 bara for a price of around 40 €/t with DMX	Pilot tested at ArcelorMittal, Dunkirk. Large-scale demonstrator (1Mt/year) to be set up with possible link to the Northern Lights project, funded under H2020 and organized around the Sleipner Platform. Demonstration phase in 2020.
	Carbon4 Pur	The unique Carbon4PUR technology will valorise steel off-gas without previous cleaning or separation of the gas components. This cross-sectoral project can transform steel mill gas streams such as CO_2 and carbon monoxide (CO) into so-called polyols – chemical key components of polyurethane-based foams and coatings that are otherwise obtained from crude oil. The decisive idea is to avoid physical separation of CO and CO_2 to make the process particularly efficient and economical. Carbon4PUR is a consortium of 14 industrial and academic partners from seven countries, coordinated by Covestro.	4-6	**CO2 emissions**: -20-60% (Secondary reduction (in carbon footprint of PUR intermediates compared to today's crude-oil based production). **Energy use**: 70% (70% reduction of process energy in the polyol producing industry, including 15-36% reduction of petrochemical epoxy compounds).	**CAPEX**: Overall budget: € 7 765 358,75, EU contribution: € 7 765 358,75. The project is funded under H2020 Spire.	Lab-based. Possible pilot at Fos-sur-Mer.

Table 3: List of Low-CO2 Steel Technology Projects

Table References: Hybrit[245], Salcos[246], GrinHy[247], H2Futures[248], SuSteel[249], Siderwin[250], Hisarna[251], Stepwise[252], IGAR[253], Torero[254], Carbon2Chem[255], Steelanol[256], FreSme[257], Valorco[258], Carbon4Pur[259]

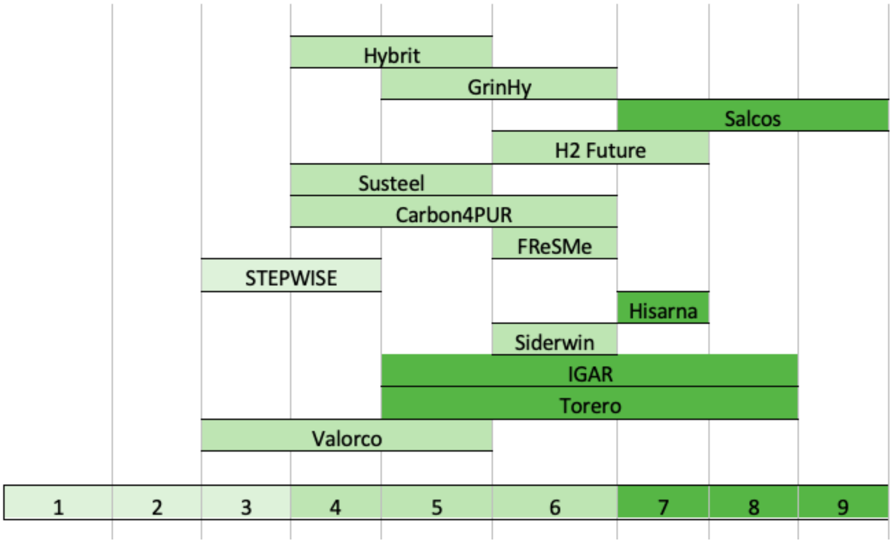

Figure 54: Low-CO2 steel production projects and their TRLs

9.3.1.4 Transition of Flemish integrated BF-BOF steelmaking – carbon integration and sector coupling

The options for transition of Flemish integrated BF-BOF steelmaking are based on public presentations[260] by the considered steel company and an interview during a site visit.

The approach considered by the Arcellormittal integrated steel plant in Flanders (Ghent) is to efficiently combine different technologies mentioned before, together with a focus of embedding steel production in the circular economy through industrial symbiosis.

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[245] Vogl et al., 2018, Hybrit 2018
[246] Dolci, 2018; Salcos, 2018; and GrInHy, 2018
[247] GrInHy, 2018
[248] Prammer, 2018; H2-Future, 2018
[249] Voestalpine, 2018
[250] Siderwin, 2018; Siderwin Work Packages, 2018; CORDIS – SIDERWIN, 2017
[251] HIsarna, 2018; Eurofer, 2017; HIsarna Factsheet, 2018; Birat, 2017
[252] STEPWISE, 2018; CORDIS – STEPWISE, 2018
[253] Prammer, 2018; Ademe, n.d.,; Chan et al., 2019; Europlasma, 2018.; Chan et al., 2019; Hensmann et al 2018
[254] Torrero, n.d.,; European Commission, 2019c; Belga, 2019; Arcelor Mittal, n.d..
[255] Carbon2Chem, 2018; The Bio Journal, 2018.
[256] Hensmann et al 2018; Arcelor Mittal, n.d.,; Steelanol, 2018; Vlaamseklimattop, 2015; INEA, 2017
[257] Bonalumia et al., 2018; Carbon Recycling International, 2019; FReSMe, 2018; CORDIS – FreSMe, 2018.
[258] Dreillard et al., 2017; Lacroix et al., 2019; Kapetaki & Miranda Barbosa, 2018; Birat, Steel, 2020, Lechtenböhmer et al., 2018.
[259] Carbon4PUR, 2018a; Cordis - Carbon4PUR, 2018; Cordis, 2017 ; Carbon4PUR, 2018b; CORDIS – SPIRE, 2017.
[260] De Maré, 2019

The first element is the substitution of coal, used in the blast furnace for the reduction of iron ore, by a combination of:

- Use of biocoal (Torrero project) derived from wood and other organic and non-organic waste via a torrefaction process
- Use of plastic waste and CO_2 (from the blast furnace) via plasma gasification (IGAR project) delivering hydrogen and carbon monoxide (syngas) to the blast furnace
- Additional hydrogen use in the blast furnace

Together this could reduce the use of coal by up to 50%.

The second element is the capturing and smart utilisation of CO, CO_2 and even nitrogen from the flue gases in steel production. This includees the conversion of CO (and CO_2) to ethanol via a fermentation process (steelanol), assisted by hydrogen to increase the yield of ethanol. The use of CO_2 and CO in methanol synthesis, also with additional hydrogen input. Possible production of naphtha via CO and CO_2 and the Fischer-Tropsch process, polyols for polyurethane and urea via the recovered nitrogen and CO_2. Finally, an interesting option to avoid emissions in agriculture would be the production of proteins that can replace animal feed via CO_2 as feedstock.

To achieve high utilisation of CO_2 an efficient CO_2 capture process will have to be deployed, something whichh is under development at the moment. Furthermore, the use of CO (and CO_2) would elminate the current power production via steel waste gases. Therefore, additional electricity demand will have to be provided, includeing for the large amounts of hydrogen required for the CO and CO_2 utilisation processes.

Finally, the remaining CO_2 emissions in steel production and the (highly concentrated) CO_2 emissions from the steelanol process will have to be captured and stored.

All these options when maximally deployed together would result in very few remaining GHG emissions from steel production (e.g. beyond 80-90% compared to around 9 Mt CO_2 emissions today).

The above-mentioned approach would imply important symbiosis between steel production and chemicals production (e.g. methanol, ethanol to HVCs), between steel and the circular economy (through the use of bio-based and plastic waste in steel processes) and possibly between steel and food production via the produciton of proteins from CO_2.

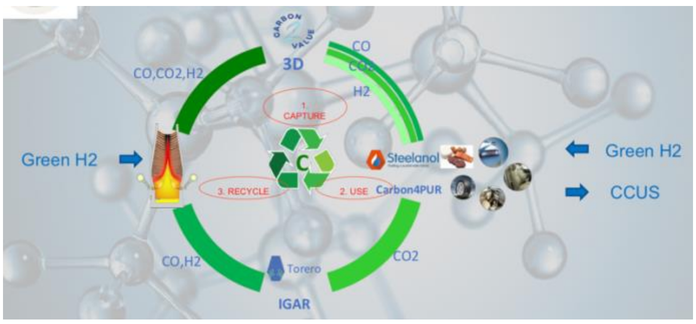

Figure 55: ArcelorMittal Carbon Integration concept (Source: De Maré, 2019)

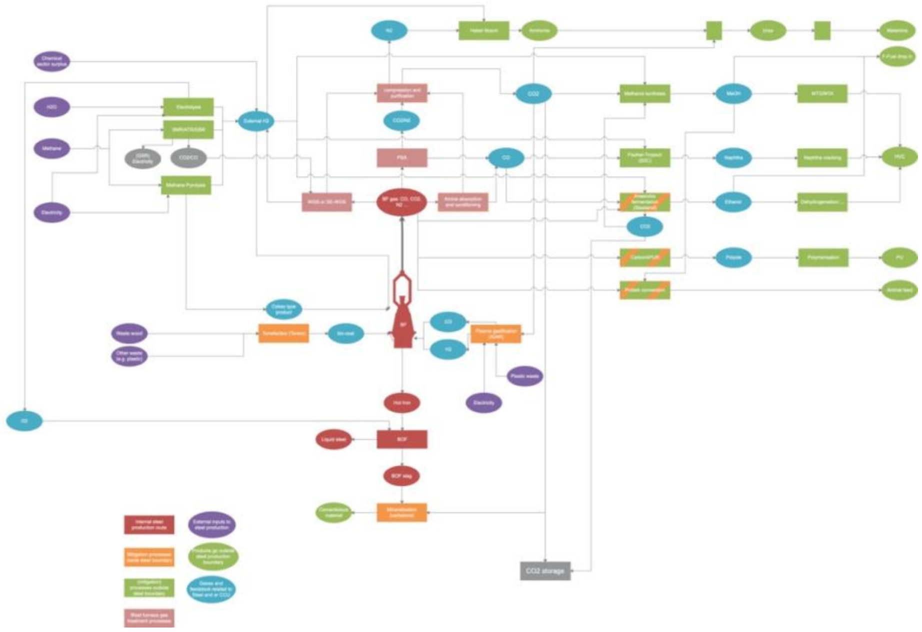

Figure 56: Detailed taxonomy of possible (partial) energy and feedstock replacement in blast furnace and utilisation of CO/CO2.

9.4 Options for deep emission reductions in other industries

This section gives a brief overview of deep greenhouse gas mitigation options for the other industrial industrial sectors (beyond chemicals, refining and steel) which do not form the central scope of this report.

In general, following the sectoral analysis in chapter 8, the smaller emitting sectors such as paper, textiles, non-ferro and food production will mainly have to consider fuel switches (mostly replacing natural gas) and related technologies to achieve emission reductions, next to continued investments in energy effiency and related technologies. This can be electrification, use of biofuels or use of e-fuels. Most of the companies in these sectors do not form part of larger industrial clusters such as Port of Antwerp, the Ghent harbour zone or the stretched zone close to the Alberkanaal. This implies that cluster strategies such as use of hydrogen, CO_2 capture and utilisation or storage or large steam network integration will not be at the direct disposal of these companies due to large infrastructure costs involved.

Electrification of heat, especially for smaller and low temperature installations could be considered on relative short term. The main bottleneck here is cost with electricity prices being much higher than natural gas on a MWh basis. Some sectors such as glass, ceramics and non-ferro require high temperature (sometimes abouve 1000˚C) here electrification is also technically challenging with intersting options being developed (e.g. microwave assisted heating in ceramics and glass), but no mature technologies to replace fossil fuel-based burners. Further R&D into high temperature applications using electricity will be important, especially if these technologies entail important efficiency gains (to off-set part of the cost difference with natural gas).

Biomass and biofuels are already applied in some sectors such as the food and paper industry. Higher use of biomass for energetic use will require a stable and price-competitive supply chain. One option could be to redirect bio-diesel production, currently aimed at the transport sector (via standards) towards (decentralised) industrial applications. This will require policy interventions at EU, national and subnational levels. Given that Flanders is an important producer of biofuels local market creation via supporting policy instruments could bring about lead markets for biofuel use in these industrial sectors.

E-fuels, discussed in detail in other chapters, can in theory relatively easy be used as alternative (e.g. e-methane which is almost identical to natural gas). However, they are not mature and produced at large scale and are expected to be much more expensive compared to natural gas at least until 2035-2040, when hydrogen from renewable electricity is expected to become competitive. The use of these fuels will also depend on the possibilty to import e-fuels (e.g. e-methanol) from areas with exceptionally low-cost renewable electricity.

Mitigation options might also be found outside the companies' perimeter. For instance, through the valorisation of low-tempature heat from the processes in the residential sector. Some of the companies in the above-mentioned sectors are located in close proximity to residential areas and can deliver excess heat (for residential hot water or heating) to this sector. This will require support by local authorities and facilitation by local infrastrucuture operators (e.g. intercommunales).

The circular economy and related business models will more and more find entrance in these sectors. The paper sector and non-ferrous metals industry in Flanders are already closely intertwined with recycling. Sometimes climate and circular economy policies might work against each other (e.g. recycling of paper/cardboard and metals (electronic waste)). This is related to the combustion of other materials that cannot be recycled and hence increase greenhouse gas emisions. Future policies aimed at either circular economy and/or climate should be integrated to maximise benefits at both sides or avoid unintentional consequences. The food and beverages industry, a major user of packaging materials, will increasingly have to be involved in the circular plastics value chain, in particular, with stronger links to the new (plastic) chemical recycling routes mentioned in the previous chapter on chemicals technologies. Here industrial symbiosis can become very important because chemical recycling will depend on economics of scale and a steady supply chain.

Notwithstanding all the above-mentioned options, it is likely that mitigation in these smaller industries towards climate neutrality will not be easy. As mentioned before, many companies will lack the infrastructure for or to important mitigation options such as use of hydrogen, CO_2 capture or integrated steam networks. But also, smaller companies might not have access to intra-company R&D resources and capital required for high-tech energy efficiency investments or new technologies enabling fuel switches. Therefore, it is recommended that in the short term, additional policy attention should go to facilitating R&D, investments in efficient climate friendly technologies and cross-sectoral initiatives in smaller industries and companies.

9.5 R&D challenges for industrial transition to climate neutrality

Based on the analysis in the previous chapters some general and specific recommendations can be formulated regarding the R&D challenges for industrial transition to a climate neutral economy. To these recommendations, a more comprehensive overview of R&D challenges for low-CO_2 and circular chemicals production is presented as extracted from the EU's Suschem strategic innovation and research agenda (SIRA) for the coming years.

The general observations on R&D challenges are:

- Many of the technologies presented are at relatively low TRL's (e.g. 3-4). It will require dedicated investments into pilot and later demonstration plants to ensure these options become available at large scale well before 2040.
- While many processes show high emission reduction potential, their efficiency from an energy and materials (e.g low yield) perspective will need to be improved significanty. This will require further investments in basic research but also the scaling up and deployment of technologies to activaty technology learning curves that come with efficiency gains (and cost reductions)
- The technologies considered are often stand alone proceses. These do not reflect performance in often complex and integrated production systems. Hence, it will be important to invest in modelling and testing of system integration of new technologies. This includees the integration with energy and materials flows in industrial production sysems.
- Finally, cost reductions both from the OPEX and CAPEX side will be essential to make innovative processes compete (even in the presence of a price on CO_2 emissions) with (global) incumbent technologies. Again, this will require accelerated deployment supported by (temporary) policy interventions such as contracts for difference (i.e. a subsidy to cover incremental production costs) until the technologies have matured enough.

Technology specific observations on R&D challenges include:

- Electrification of high temperature heat could prove a very efficient and climate friendly technology. However, it hasn't advanced enough for commercial deployment on short or even medium term. The challenge here is to develop processes that are at least 40-50% more efficient vis-à-vis heat via natural gas as to make up part of the cost disadvantage of electricity.
- Energy and cost-efficient (gas and liquid) separation technologies will remain important as to improve both the yield and energy needs for e.g. HVC production and CO_2 capture.
- Catalysts, both their chemical and phyisical design, will become even more important multi-purpose technologies due to their application in almost all low-CO_2 chemicals processes (e.g. CO_2 capture, synthesis of methanol, plastics recycling, …). Accelerated development of new, durable, (if possible) cheap and non-critical raw materials dependent catalysts will be crucial. Hence, investing

more in dedicated laboratories that have access to advanced machine learning tools for faster validation of catalytic properties will be a no-regret R&D investment.

- Materials efficient use of biomass, i.e. focussing on highest possible HVC (or HVC equivalent) yields per tonne of input, should become a guiding factor in bio-based chemicals R&D. This includes development of innovative processes, but foremost the evaluation of system integration in bio-refineries which combine different biomass conversion and energy recovery technologies.
- For carbon capture the main R&D challenge is reduction of OPEX, mostly related to additional energy use for the capture process. Here the introduction of performance benchmarks (e.g. < 2 GJ/t CO_2 captured) could offer important guidance to future R&D investments.
- Given that carbon capture is likely to be a critical technology for chemicals, refining and steel production and that it would come with high additional energy needs it is essential that excess industrial heat, currently not used, is integrated with carbon capture processes. Hence, processes such as chemical heat pumps that can bring <100°C waste heat to the required temperature range for some capture processes will be essential for efficient and integrated capturing of CO_2 in existing industrial processes.
- Furthermore R&D into technologies that facilitate the symbiosis between heat and electricity will be important for large scale industrial applications. For instance, the use of industrial heat to drive more efficient high-temperature electrolysis.
- Industrial cluster level system integration of carbon capture will require additional R&D to ensure that the diverse CO_2 sources with different concentrations can be integrated cost-efficiently into a carbon capture and transport hub.
- Similarly, further R&D into the integration of (new) industrial processes in the energy system will be critical on the road to full and efficient deployment of new process technologies. For instance, advanced use of industrial demand response, options for energy storage (e.g. in materials and fuels) via industrial processes, recovery of excess heat for electricity production, …

The above-mentioned lists are by no means meant to be complete but reflect some of the main findings and concerns that followed the technology analysis in the previous chapters.

For a more complete assessment of technological challenges in chemicals production the SUCHEM SIRA provides a comprehensive list. The table below is an extraction of the challenges identified by SUSHEM related to low-CO_2 chemicals production, circular economy and bio-based chemicals.

Technology	Horizontal Challenges
Bio-based Chemicals and Materials	• Management of materials resources, feedstock availability and land use; • Higher cost of production in many product categories, driven by high feedstock prices and/or due to technologies that have not yet been optimised; • Biomass feedstock composition variability increases the complexity of upstream and downstream processes with especially challenging purification steps; • Comprehensive circular strategies to design bio-based materials for recyclability; • Biodegradable materials provide unique properties in specific applications such as the collection and treatment of food waste, albeit environmental claims regarding biodegradability or compostability should comply with appropriate standards. Harmonised rules for defining and labelling compostable and biodegradable plastics are being created at European level.
Membranes	• Developing new materials for enhancing the membranes' selectivity and performance; • Reduction of the energy required for membranes production.
Electrochemical, Electrocatalytic and Photo-electrocatalytic Processes	• Process optimisation of processes, in particular catalyst design and optimisation (see Enabling CO_2 valorisation via catalysis; • Reactor design and engineering to achieve improved reaction control and address specific requirements of the feedstock and energy source.
Power-to-Heat	• Energy efficiency of electricity-based heating systems for low and high temperature heat; • Integration of novel heating systems with renewable energy electricity sources; • Materials for high temperature heating.
Hydrogen Production with Low-carbon Footprint	• Further scale up of the existing technologies (e.g. alkaline, PEM); • Improve electrical efficiencies of the electrolysers technologies; • Robustness of processes for low-carbon hydrogen production; • Disruptive technologies to enable large-scale production of hydrogen with a low-carbon footprint independently of renewable electricity availability.
Power-to-chemicals	• Performance improvements beyond energy efficiency, to improve process metrics; • Catalyst design (see 'Enabling CO_2 valorisation via catalysis'; • Reactor design and engineering to achieve improved reaction control; • Further scale up of the technologies developed; • Higher production cost than fossil-based route due to high OPEX
Catalysis	• Rational design of new catalysts, combining computational tools, combinatorial design and high-throughput screening; • Improved catalyst characterisation techniques/ methods; • Novel characterisation tools for in-situ monitoring of reaction and catalyst over time; • Advanced catalyst production techniques e.g. 3D-printing to promote intensification of catalytic processes; • New reactor design: e.g. coated microchannel reactors, monolithic reactors, coated heat exchangers; • Intensification of catalytic processes to develop and design more efficient processes (e.g. integration of the catalyst to the reactor structure; • Catalytic processes intensification by combining reaction and separation (e.g. by membranes); • Catalytic processes optimisation for application of non-conventional energy forms (e.g. ultrasound or microwaves); • New catalyst concepts and formulations with versatile applications in catalysis, including integrating new types of materials; • Multifunctional catalysts, combination of homogeneous and heterogeneous catalysts design.
Enhancing biomass catalytic valorisation	• Catalyst or biocatalyst stability against poisoning and coke precursors which may be present in biomassbased feeds; • Catalysts with improved properties (noble metals free, no leaching) through rational design; • New catalysts and routes for preventing the formation and processing of by-products from biomass conversion (e.g. black liquor); • Improvement of efficiency, productivity and sustainability when compared to current benchmark processes; • Process intensification and continuous processes are needed to reduce costs and environmental impact.
Enabling waste valorisation via catalysis	• Increase catalyst robustness given the fluctuation and diversity of plastics waste as feedstock for selective catalytic conversion processes by combining the physicochemical characterisation of the waste and a knowledge-based approach development of all process steps; • Catalytic processes should be focused on selectivity, large operating window, stability, loading of the selected catalysts and regeneration potential.
Enabling CO_2 valorisation via catalysis	• Development of highly active/efficient and selective catalysts given the low reactivity of the CO_2 substrate; • Development of catalysts less prone to poisoning enabling the utilisation of less purified CO_2 streams; • Catalysts enabling CO_2 valorisation processes at lower temperature and/or pressure; • New heterogeneous and homogeneous catalyst for direct CO2-to-chemicals and polymers; • Catalysts for direct CO2 electrochemical and photo electrochemical reduction reactions; • Development of catalysts based on abundant metals.
Light hydrocarbons catalytic valorisation	• More robust, selective, flexible and aging-resistant catalysts and catalytic processes will allow to better handle feedstock variability; • Scalable catalyst manufacture with reduction of the consumption of critical raw materials and preferably starting from earth-abundant and accessible raw materials.
Engineering of microorganisms and enzymes (in silico and in vitro)	• Adapting microorganisms to process conditions implies inverting the state-of-the-art paradigm of process adaption to microorganisms.
Bioprocess development (upstream & downstream)	• Low space time yield vs. transformation efficiency and low contamination necessitate process intensification where new reactor concepts are needed specifically for IB processes; • High cost of biocatalysis applicable for processes for high price / low volume (specialty) but also low price / high volume (bulk) chemicals; • Separation and purif ication technology developments specifically for IB; • Enabling the automation and digitalisation of biotechnological processes.

Bioprocess development (biomass and waste valorisation)	• Adapt upstream and downstream processes to sustainable biomass feedstock availability; • Ecoefficiency studies to identify optimal valorisation of biomass and waste feedstock; • Develop and optimise viable processes for the conversion of biomass into substrates suitable for fermentation and bioconversion (e.g. enzymatic, physical, chemical, or a combination).
Waste Valorisation Process Technologies	• Waste composition complexity, variation over time, access to homogeneous waste through improved upstream collection, logistics, sorting, separation, and pre-treatment; • Removal of impurities such as colourants and additives, including hazardous substances, causing issues with the waste valorisation processes; • Physicochemical and mechanical characteristics of recyclates compared to virgin materials; • Control of degradation by-products upon recycling; • Reducing energy intensity (and related CO_2 emissions of recycling processes) through process optimisation.
Chemical valorisation of secondary biomass sources	• Management of materials resources, feedstock availability and land use; • Higher cost of production in many product categories, driven by high feedstock prices and/or due to technologies that have not yet been optimised; • Biomass feedstock composition variability increases the complexity of upstream and downstream processes with especially challenging purification steps; • Comprehensive circular strategies to design bio-based materials for recyclability; • Biodegradable materials provide unique properties in specific applications such as the collection and treatment of food waste, albeit environmental claims regarding biodegradability or compostability should comply with appropriate standards. Harmonised rules for defining and labelling compostable and biodegradable plastics are being created at European level. • Cost competitiveness improvements, in particular for drop-ins; • Improved biotech process optimisation for polymers production over biomass feedstock flexibility (composition variability); • Robust biocatalyst design against upstream and downstream contaminants. • Catalyst or biocatalyst stability against poisoning and coke precursors which may be present in biomassbased feeds; • Catalysts with improved properties (noble metals free, no leaching) through rational design; • New catalysts and routes for preventing the formation and processing of by-products from biomass conversion (e.g. black liquor); • Improvement of efficiency, productivity and sustainability when compared to current benchmark processes; • Process intensification and continuous processes are needed to reduce costs and environmental impact.

Table 4: Important R&D challenges for low CO_2 and circular chemicals (Source: SUSCHEM SIRA, 2019)

9.6 Industrial symbiosis

Low CO_2 technologies and pathways show an important potential for industrial symbiosis between industrial and non-industrial sectors through mutual materials, energy flows or by dual use of low-CO_2 technologies in other sectors.

Crude oil refining already has a high level of integration with petrochemicals production by producing feedstock for chemicals production or production of basic chemicals. A number of technological options for greenhouse gas mitigation in chemicals production will also be highly relevant for refining. For instance, zero CO_2 hydrogen production, use of plastic waste for production of feedstock, bio-based fuels, electrification of boilers, CCS and CO_2 utilisation e.g. for production of e-fuels.

Major opportunities for deep industrial symbiosis between *steel* and chemicals production are possible. From the side of steel production, the use of waste gases from cokes and iron and steel production offers the potential of feedstock for large volumes of basic chemicals production (e.g. via ethanol or methanol). Furthermore, plastic waste can be used (e.g. via plasma gasification) as reducing agent in hot iron production. Future low-CO_2 steel production will also depend on large volumes of zero-CO_2 hydrogen production (either for reduction of iron ore or for higher levels of utilisation of steel waste gases). Hence zero-CO_2 H_2 technology will also be relevant for steel producers. Methane pyrolysis, for instance, can deliver both H_2 and carbon that can be used in iron ore reduction. Finally, carbon capture technologies will play a role in future mitigation of steel sector and chemical sector emissions.

Part of the Flemish *food and drinks industry* already has a strong link with chemicals production either through being producers of plant-based oils or by the use of by-products in chemicals production (e.g. ethanol and citric acid). Depending on market conditions and the regulatory environment there can be a shift from biofuels towards bio-based chemicals. The food industry will be able to benefits from technological innovations that help reduce emissions from (steam) boilers e.g. electrification, biomass/biogas, fuel cells and heat pumps. Production of food and drinks can, if located close to major chemicals/steel producers, benefit from cross-company integrated steam networks and hence forego use of on-site boilers. Futhermore, the important use of plastics packaging in food and beverages production offers options of futher industrial symbiosis with advanced chemicals plastic recyling via the recovery of packaging waste. Finally, advanced use of CO_2 includes the possible production of proteins which can be applied in animal feed or as meat replacement for human consumption.

Pulp and paper production, similarly to food and drinks production, will require (cost-effective) innovations with regard to heat/steam production. Heat integration with other major heat consumers is possible in theory but limited because of location of most paper/cardboard producers. On the other hand, cardboard and paper production can become a low-T heat provider to other sectors (in particular buildings sector) via heat-networks driven by waste heat from steam for paper production. Paper and cardboard producers working with recycled materials could consider technological innovations related to recovery of materials/energy from waste streams (input/output).

There is potential for interesting deeper symbiosis between *waste* treatment, recycling and incineration and the chemicals and steel industry. The waste treatment industry (Indaver) is seen as frontrunner in Flanders in the area of chemical recycling with potential of high level/value integration of chemical-plastic recycling in the Port of Antwerp. Similarly, the sector is a frontrunner in enabling the development of a large integrated steam network in the Port of Antwerp (Ecluse project), replacing decentral boilers and reducing emissions by economies of scale. Finally, MSW can become important feedstock for chemicals/steel production e.g. via gasification/torrefaction.

Symbiosis between the industrial and energy sectors, and in particular power sector is widely present, in particular through the use of large and smaller scale combined heat and power (CHP) installations. Deploying carbon capture (and utilisation and storage) to CHP installations will on short term not be straightforward and costly (due to the low CO_2 concentration in CHP flue gases). However, industrial symbiosis between energy and industry will be essential towards climate neutrality due to higher electricity needs for industry (e.g. electrification of boilers, process installations, carbon capture and H_2 production). Furthermore, heat and steam demand will still be high from industry side regardless of technologies used. The following elements could be considered:

- Direct access to renewable electricity (e.g. offshore wind) not on site together with maximising on site renewable electricity deployment.
- Integrating electrification of processes with variable renewable electricity through demand response and where possible storage at industrial sites/in products
- Develop efficiency electricity generation with CCS (Allam cycle) using CO_2 networks in proximity.
- Use of new processes that can co-produce electricity and heat and/or products such as fuel cells
- Evaluate highest value use of biomass for energy versus feedstock
- Facilitating business models for cluster level heat/steam generation and networks
- Find use for low-T/P waste heat outside of industry such as the residential sector.

Industrial cluster (e.g. port) scale industrial symbiosis will have to be be strengthened using the deployment of low-CO_2 technologies, hydrogen production and new steam/heat and infrastructure:

- Extended steam networks with fewer large boilers generating steam. This can reduce (overall) costs of CO_2 capture given that capture technology will only have to be deployed at fewer locations and at larger scale, likely leading to (overall) cost savings. For users of steam the use of chemical heat pumps can locally assist with bringing steam from the network at higher T and pressure, if required.
- A CO_2 pipeline network would offer infrastructure for captured CO_2 and hence enable investments in CO_2 capture or, at later stage, utilisation. It can be considered if supercritical CO_2 can be used as more efficient working fluid vis à vis steam.
- The construction of an extended H_2 network and flexible access to the network.

- Integration with electricity production incl. renewable electricity and power production with CCS (Allam-cycle).

On a broader scale, the important industrial clusters in Flanders form part of a maritime linked industrial eco-system. Many if not most of the energy and materials supplied to industries such as steel, chemicals and refining arrive by ship. These logistic routes will also be important for future new supply chains (e.g. methanol). The maritime sector is expected to be essential for the industrial transition, in particular given its potential to supply the northwestern European industry with large amounts of renewable electricity via offshore wind. Wind-Europe recently estimated an economic potential of up to 6000 TWh electricity at prices below 60 EUR/MWh. This is twice the current EU electricity demand. It can hence not be stressed enough that the Flemish industrial transition (including its expected higher electricity demand) must ensure access to affordable, secure electricity. Immense deployment of offshore wind in northwestern Europe seems essential for the industrial transition to climate neutrality. Here industrial symbiosis can drive an energy and industrial revolution given that the deployment of offshore will require large amounts of steel, non-ferrous metals and chemical products, giving a boost to regional manufacturing hubs especially these located close to maritime environments. Similarly, the storage of CO_2 will require cooperation with countries that have access to storage sites located below the seabed. Hence, in Flanders infrastructure and logistics will need to be developd to access a variety of storage sites. This will require investments in dedicated shipping infrastructure and (liquified) CO_2 storage for transport to permanent storage or use of CO_2.

9.7 Possible pathways for Flemish industry

9.7.1 Introduction and SWOT

This section considers possible pathways for energy intensive industries towards climate neutrality. The pathways use the information gathered in the previous sections, including:

- The current state of Flemish energy intensive industries (e.g. emissions, energy use and value chains)
- The possible technological options for deep greenhouse gas emissions mitigation
- Information on industrial symbiosis and cluster infrastructure needs
- Input from interviews with 20 EU ETS companies in Flanders on prospects for transition to climate neutrality

To this a previously developed and slightly updated SWOT[261] is added to improve the insights for the starting point of possible pathways.

[261] Wyns et al., 2018b

Strengths	*Weaknesses*
• *Central geographical location* • *Excellent connectivity (logistics)* • *At the core of European value (& supply) chains* • *Clustering of production plants/processes and process optimisation (esp. Chemicals & Refining)* • *Strong presence of large multinationals creates positive spill-overs for smaller (local) companies in industrial clusters* • *Refining has due to Integration of world-class stream cracking installations and availability of surplus coking a 'Must Run' status* • *Highly skilled labour force* • *Strong reputation for research and business expenditure on R&D (BERD)*	• *High energy cost related to EU policy (exposure to prices)* • *Most (large) investment decisions are taken by multinational companies with decision making centres outside of Flanders.* • *Relatively high labour costs* • *Regulatory complexity especially for multinationals* • *Open economy and location → vulnerable to international trade disruptions* • *Need for more and updated infrastructure given status as a major logistics hub*
Threats	*Opportunities*
• *Global sectoral developments (US shale gas & shale oil, new investments in Middle East, overproduction in emerging economies like China)* • *EU & global trade disruptive events (e.g. Brexit, US mercantilism, COVID19)* • *Disruptions during the transport and power sector low-carbon transition. The first might weaken the position of refined oil production and hence the link with petrochemicals* • *Industrial low-carbon technologies deployment → (significantly) higher electricity demand → demand for investments in low-carbon power production* • *Circularity → lowered demand of basic products/materials* • *EU ETS → (future) higher CO_2 prices → more carbon exposure → uneven global playing field*	• *Energy/power-sector transition → industrial demand response/storage opportunities* • *Well placed industrial clusters offer opportunities for industrial symbiosis and better economic resilience in a low-carbon economy* • *Circularity → new business models and higher value-added products and services* • *Instrumentalise Know-how and public supported R&D (e.g. moonshots) via demonstration of low-CO_2 technologies in Flanders* • *Create lead markets for low-CO_2 products and technologies in Flanders via a mission oriented industrial policy*

Table 5: SWOT analysis of Flemish industry in context of transition to climate neutral economy.

To assess the possible pathways the conceivable actions are divided into the following time slots:

- Actions to be taken on short term
- Activities in the next decade
- Activities in the period 2030-2040
- Activities in the period 2040-2050

It is not the goal here to present a full-fledged roadmap (including expected technology shares). This part of another modelling-based deliverable in this project. Hence the pathways and activities shown below should be considered as illustrative examples.

Strategically it important to use the strengths of the Flemish industrial ecosystem as a starting point. This includes:

- Location: a key strength of industry (in particular industry located in major clusters) if of course location with easy access to a range of energy sources, raw materials and access to logistics (e.g. shipping). This includes the ability of (publicly owned) port authorities to coordinate and help with execution of (infrastructure) projects.
- value chains and industrial symbiosis: the presence of down- and upstream value chains and industrial symbiosis where companies exchange materials/energy/waste streams
- Networks: the presence of dense and large networks of natural gas, hydrogen and petrochemicals
- Efficiency and process optimisation: a rich history and local know how with regard to process optimisation which contributed to keep industry globally competitive

These factors should be used optimally when planning and developing transition pathways for the Flemish energy intensive industry.

9.7.2 Actions in the short term

The main recommendation on the short term is to prepare for large industrial technological demonstration and infrastructure projects that are deemed essential for transition of industry and can be eligible for significant EU funding that becomes available now.

Based on the technology options assessed before, the preparation for the development of carbon capture and transport infrastructure in Port of Antwerp can be seen as a priority activity on short term. CC(U)S will be part of the technology portfolio solutions because:

- Some processes are almost capture ready.
- It will be part of mix of technology solutions and can help to not become highly dependent on a single energy or feedstock vector (e.g. very high electrification or biomass use).
- The infrastructure is forward compatible with future CO_2 utilisation and shorter-term storage of CO_2

Other projects with high relevance are:

- Explore use of integrated steam networks in industrial clusters given that this can replace smaller boilers where carbon capture would be more costly
- Reverse logistics and processes for chemical plastic recycling given that these are mature or close to commercialisation and would fit well inside the Flemish chemicals value chain (with its high focus on polymers)
- Demonstration of blue and green H2 production
- Reinforced connections to green electricity (e.g. direct line offshore)
- Detailed mapping of energy and secondary raw material flows inside and between sectors to explore supra-sector GHG mitigation and efficiency gains to explore full gains of industrial symbiosis (incl. link with e.g. waste, buildings and agriculture).

- Early focus on the challenge of reducing emissions in companies outside industrial cluster (where emissions are mostly due to fossil fuel combustion for generation of heat/steam).

9.7.3 Possible actions in next 10 years

The period 2020-2030 will be explorative but includes choices that are forward compatible with most future patways. Important is the development of CO_2 infrastructure (as argued above) but also the demonstration of possible essential technologies for achieving climate neutrality, the first steps in industrial symbiosis between steel and other sectors and chemical recycling. Futhermore, technologies that are not viable at the moment can be explored given their possible large potential in next decades when these might become less expensive due to innovation, learning curves or evolution of prices of feedstock energy.

Examples

Pathways	Possible activities in period 2020-2030
Carbon capture and storage or utilisation pathway	• Construction of CO_2 network (Antwerp@C) with linking of concentrated CO_2 sources and storage (outside of Fanders). This can result in reduction of +/- 2 Mt CO_2 • Development of blue H_2 project linked to CCS network (can be included in above e.g. via existing steam methane reforming+CCS or new type blue H_2 production) • Experiment/advance research with capturing of low CO_2 concentration sources • Develop Blue H_2 (i.e. H2+CCS) for refining, can be linked to CCS project mentioned above. Options are for instance large H2 production installation with CCS feeding H_2 network or decentralised smaller H2 production with CCS. • Demonstration of CCU chemicals/e-fuels production [1,000-10,000t/a] • Demonstration of CCU in steel production to ethanol/chemicals [10,000 t/a]
Electrification and process efficiency pathway	• Start with electrification of small low T boilers including hybrid systems that can act in (power) demand response systems. • Demonstrate (depending on state of technology in period 2020-2030) electrification of high T heat. • Demonstrate at large scale 1-2 new catalytic based chemical processes with significant lower CO_2 and energy footprint and with possibility of electrification [10,000-100,000 t pa]
Biobased pathway	• Demonstrate bio-based aromatics aromatics production • Furher deploy bio-based/waste to energy esp. in smaller companies not located in large industrial clusters. In particular food sector could further deploy gasification of biomass waste. • Demonstrate bio-based waste used in steel production • Evaluate techno-economic potential of large scale (ligno-cellulosic based) bio-refinery and link with possible (existing and new) value chains
Circular economy pathway	• Develop/demonstrate chemical recycling of plastics on medium to large scale [capacity 10,000-100,000 t/a] secure stable supply chain (e.g. through policy/regulatory intervention) • Demonstration of circular chemicals/waste in steel production

Energy related initiatives	• Advance research and know-how on advanced reactor designs and process integration/optimisation for low- CO_2 processes and electrification of processes • Explore additional H_2 production/supply to be used in steel sector for e.g. CCU • Investigate investment in high efficiency gas turbines with CCS (such as Allam cycle) for electricity production to energy intensive industries (e.g. linked to CO_2 network) or cogeneration of electricity with hydrogen and CCS (via GSR) to secure affordable low CO_2 electricity. • Evaluate the direct connection of large industrial clusters to large scale renewable electricity (e.g. off-shore wind) • Further integrate renewable electricity production on industrial sites outside of large industrial clusters, where possible • demonstrate green H_2 production (electrolysis) and integration with e-fuels/chemicals production use in steel production • Evaluate the deployment cluster level integrated steam networks (e.g. following example of Ecluse project in Antwerp harbour) including replacement of smaller boilers with larger installations that are linked to CCS network and/or produce steam via biomass. This can be considered together with distributed use of chemical heat-pumps to achieve locally needed steam at right T and P. • Invest in low-T heat networks (where technically and economically viable) near industrial plants not located in clusters. Low-T heat will be used in tertiary sector to lower emissions there. • Research the valorisation of by-products in chemical processes which are currently incinerated for use of heat (e.g. steamboilers). This issue will have to be addressed in case of electrification of large industrial process plants such as steam-crackers in following decades. • Research use of supercritical CO_2 as efficient working fluid e.g. in small scale pilot linked to CO_2 network. • Demonstrate techno-economic viability of CO_2 free steam/heat production in smaller industry located outside of cluster. [e.g. electrification, biomass, fuel-cells, e-fuels, e-gas, …] • Demonstrate the recovery of low-T industrial waste heat via e.g. thermal regenerative batteries or related to exothermal chemical processes.
Other activities	• Full reduction of N_2O emissions in e.g. caprolactam production in period 2020-2030. [-400,000 t CO_2-eq]

Table 6: Examples of activities that can be considered in 1st phase of transition (2020-2030)

9.7.4 Actions in the period 2030-2040

The deployment of the pathways in the period 2030-2040 will depend on state of technology (TRL) on relative cost of feedstock and energy carriers and development of supply chains and networks. The pathways listed below will hence have to be evaluated against these conditions. Hence, it is likely that not all below-mentioned pathways will see maximal deployment.

Examples

Pathways	Possible activities in period 2030-2040
Carbon capture and storage or utilisation pathway	• Maximise potential for CCU related to steel production (waste gases) with production of e-fuel/platform chemicals (ethanol, methanol) [max. 3 Mt]. This will require major H_2 inputs via autoproduction on site and/or imported. [Given that steel production in Flanders is in most advanced stage currently with regard to CCU, it is expected first major deployment happens there]. • Implement carbon capture technology (and transport) for steel production for remaining CO_2 emissions. [options for CO_2 transport include shipping or pipeline connection to Antwerp, Zeebrugge or Terneuzen] • Develop CCU capacity for expected new market for bunker e-fuels fuels shipping and avation • If economically viable invest in e-fuel (methanol/ethanol) to olefins production capacity [range: 1Mt/a – 25% of current olefins production. E-fuels can be sourced from above mentioned CCU projects (e.g. steel). This will depend on market and regulatory environment and H_2 supply]. • If Antwerp CO_2 network operational and storage secured, consider extending blue H_2 production to supply CCU. [depends on H_2 market conditions but not expected to have large import at low cost in that period] • Build First of a Kind (FOAK) low CO_2 concentration capture installation
Electrification and process efficiency pathway	• Demonstrate e-cracking at large scale [100-500kt HVC/a, 10% of current Flemish HVC production] • If demonstration of new (low energy/CO_2) catalytic chemical processes successful in period 2020-2030 deploy 1-2 at industrial scale and electrify. • Full switch of small (<< 1MW) boilers to electricity • Demonstrate high T electrification integrated in production process [this demo is possible in sector outside of cluster e.g. glass, ceramics, ..]
Biobased pathway	• Re-orient bio-fuels production to aviation and shipping [expecting regulatory driven new market] • If techno-economically possible develop large scale lignin to BTX plant [100 kt BTX/a] • If techno-economically possible extend bio-refining to provide e.g. 5-10% of chemicals feedstock (e.g. ethanol) [e.g. up to 300 kt/a] • Fully utilise bio-based/waste to energy in Flanders esp. in smaller companies not located in large industrial clusters. In particular food sector could further deploy gasification of biomass waste.
Circular economy pathway	• Chemical recycling of plastics grows to 1 Mt/a [approx. 80% to be used in feedstock or monomers for polymers] – supply chain stable and optimised [including sourcing plastic waste outside Flanders] • Expansion of waste/plastic use in steel sector

Energy related initiatives (depending on relative costs natural gas, electricity, CO_2, …)	• Activate steam network in large industrial clusters and suppress small boilers that are not converted to electricity. Use large scale steam production installations with CCS. Deploy chemical heatpumps where needed • Extend H_2 production (linked to CCU deployment): combination of green, blue and turquoise (methane pyrolyisis) H2. Replace all H2 production in refining with these units. • Extend use of supercritical CO_2 // thermal regenerative batteries // fuel cells [if technically/economically viable] • Develop + extend infrastructure Linkages with other large industrial clusters outside Flanders [e.g. CO_2/H_2] • Depending on evolution in EU electricity markets invest in additional allam cycle CCS and/or GSR H_2-electricity + CCS • Reinforce transmission of electricity at locations where electrification is expected to increase. • Maximise deployment of low-T heat grids near industrial producers located outside of industrial cluster and near other sector with appropriate heat demand • Further invest [R&D and demo] into low-CO_2 solutions for smaller industrial producers outside large industrial clusters.

Table 7: Examples of activities that can be considered in 2nd phase of transition (2030-2040)

9.7.5 Actions in the period 2040-2050

The activities in this timeline will of course mostly depend on the strategic choices of previous decade and on evolution of technology and energy costs. Again, the pathways listed below will hence have to be evaluated against these conditions. Hence, it is likely that not all below-mentioned pathways will see maximal deployment.

Examples

Pathways	Possible activities in period 2040-2050
Carbon capture and storage or utilisation pathway	• Low CO_2 concentration emissions can be captured at acceptable cost and technology is fully deployed in industrial clusters, refining and steel production [up to X% of Flemish industrial emissions] • CCU e-fuels production increased and delivers up 100% of bunker fuels and 50% of carbon feedstock for chemicals production. [depends on availability/price of low CO_2 H_2 production]
Electrification and process efficiency pathway	• Naptha steam cracking is fully and propane dehydrogenation is partially electrified [but only if energy efficient e processes are fully mature] • All boilers <20 MW electric • New chemical processes with low-CO_2 and energy use replace existing installations [low OPEX justifies CAPEX investment]
Biobased pathway	• Biobased processes deliver 20-50% of platform chemicals [depending on supply chain] • Biobased energy with CCS [given that low concentration CC is available] is deployed leading to negative emissions [or compensation remaining emissions in industry]

Circular economy pathway	• Flanders become's one Europe's main hubs for chemical recycling of plastics [delivers +50% of chemical sector feedstock/monomers] • Steel production integrates large scale bio and municipal solid waste in production process
Energy related initiatives (depending on relative costs natural gas, electricity, CO_2, …)	• Securing low CO_2 H2 through [smart/economic] combination of domestic blue/green production, import via pipelines [Germany/Nl/Fr] and shipping, likely not as H2 but in other liquid molecules with higher energy density. • Access (+transmission capacity) to large quantiy of renewable electricity via integrated EU/EEA grid/market [e.g. large offshore wind deployment in NW Europe] • Large scale demand response in industry via flexible electrified processes • Full integration of Flemish industrial clusters in trilateral low-CO_2 pipeline system • Full industry-energy system optimisation: 1) inside large industrial clusters [e.g. steam/CO_2 networks] 2) with other sectors if not possible in cluster • Industrial scale storage of energy/electricity – sometimes inside basic materials produced by industry
Other elements	• Full deployment of sector coupling: energy-industry, industry-waste, intra-industry, … • Remaining industrial emissions are compensated through e.g. biobased CCS • Smaller industrial producers that find no cost-effective solution for deep GHG mitigation or reducing emissions in other sectors (e.g. use of waste heat) will be assisted [financially/logistically] to relocate inside larger clusters.

Table 8: Examples of activities that can be considered in 1st phase of transition (2040-2050)

10. International comparison (UK, DE, FR, NL)

10.1 Introduction

This chapter will draw a comparison of industry in Flanders with that of four key neighbouring European countries – Germany (DE), France (FR), The Netherlands (NL) and the United Kingdom (UK) - along three parameters: GHG emissions, GVA and employment The sectors assessed here are listed below, allowing a direct comparison between Flemish industries and those of the neighbouring countries.

These sectors are:

- Manufacture of food products, beverages and tobacco products (10-12)
- Manufacture of textiles, wearing apparel and leather products (13-15)
- Manufacture of wood and of products of wood and cork (except furniture); manufacture of articles of straw and plaiting materials (16)
- Manufacture of paper and paper products (17)
- Manufacture of coke and refined petroleum products (19)
- Manufacture of chemicals and chemical products (20)
- Manufacture of other non-metallic mineral products (23)
- Manufacture of basic metals (24)

All the data presented in this chapter has been extracted from the European Commission's EUROSTAT statistics database[262] unless stated otherwise.

The chapter also presents the most prominent policy responses of the four countries.

The chapter next assesses in detail a large selection of the most reliable European roadmaps and studies on decarbonization of the industrial sectors. From these, lessons are drawn for sectoral decarbonization in Flanders.

Finally, an indepth overview of the neighbouring Industrial clusters connected to Flanders is presented. Existing and potential interlinkages between these clusters and a (non-exhaustive) list of examples of cooperative projects are explored along with prospects for cooperation at regional and European levels.

[262] Extracted from Eurostat (GVA figures: nama_10_a64, Employment: nama_10_a64_e, GHG emissions: env_ac_ainah_r2)

10.2 Comparison Table

Comparison of Neighbouring Countries[263]					
	Flanders	**FR**	**UK**	**DE**	**NL**
Economy-wide Emissions (2018, MtCO2-eq)	78	332.3	379.1	742.2	173.3
EII Emissions (2018, MtCO2-eq)	22	84.3	63.6	158.6	46.1
EII Emissions (% economy)	28.2%	25.7%	16.8%	21.4%	26.6%
EII Emissions % Change 2008-2018	-3%	-29%	-35%	-8%	-3%
Total EII Emissions Intensity [kt CO2/Mn EUR] (2016)	1.026	0.848	0.774	0.806	1.206
Emissions Intensity (% Change 2008-2016)	-20%	-29%	-42%	-24%	-12%
Economy-wide GVA (2018)	EUR 0.23tn	EUR 2.1tn	EUR 2.2tn	EUR 3tn	EUR 0.7tn
Total EII GVA (% of Economy, 2016)	EUR 15.5bn (9.1%)	EUR 103.7bn (5.2%)	EUR 89.9bn (4.1%)	EUR 195.4bn (6.8%)	EUR 37.6bn (5.9%)
EII GVA as % of Economy (% Change 2008-2016)	-7%	-6%	-2%	-4%	-1%
Economy-wide Employment (2016, Persons)	2.7 mn	27.6mn	31.7mn	43.7	8.9mn
EII Employment (% of Economy, 2016)	7%	4.7%	3.4%	6.1%	3.3%
EII Employment (% change 2008-2016)	-13.9%	-12.8%	-13.4%	-7.9%	-8%
Sectors					
Chemicals	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	8.7	20.9	12	30.9	21.3
Emissions (% Change 2008-2018)	-5%	-28%	-37%	- 15%	+9%
GVA (% of Economy) (2016)	3.1%	0.9%	0.6%	1.7%	1.6%
GVA as % of Economy (% Change 2008-2016)	4.9%	12%	18%	3%	-5%
Direct Employment (% economy, 2016)	1.19%	0.4%	0.3%	0.8%	0.5%
Direct Employment (% change 2008-2016)	-15%	-12.1%	-29.9%	-5.6%	-4.6%
Basic Metals	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	5.14	18.1	11	43.5	7
Emissions (% Change 2008-2018)	-3%	-24%	-58%	-10%	-7%
GVA (% of Economy) (2016)	0.92%	0.3%	0.2%	0.7%	0.3%
GVA as % of Economy (% Change 2008-2016)	-21%	-41%	-31%	-56%	-41%
Direct Employment (% economy, 2016)	0.65%	0.3%	0.2%	0.6%	0.2%
Direct Employment (% change 2008-2016)	-22.1%	-21.7%	-20.6%	-11.4%	-9.4%
Coke & Refined Petroleum	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq) [refining]	6.1	11.4	14.6	22.8	10.2
Emissions (% Change 2008-2018) [refining]	-3%	-47%	-23%	-5%	-14%

[263] For UK, Nl, FR, DE the data was extracted from Eurostat (GVA figures: nama_10_a64, Employment: nama_10_a64_e, GHG emissions: env_ac_ainah_r2). For Flanders the emissions data source is Vlaamse Overheid, nieuwsbrief emissierechten, 2020 and VMM, 2020 and the socio-economic data source is the NBB.

GVA (% of Economy) (2016)	0.67%	0.1%	0.1%	0.2%	0.2%
GVA as % of Economy (% Change 2008-2016)	-9.3%	11%	-30%	29%	-42%
Direct Employment (% economy, 2016)	0.14%	0.0%	0.0%	0.0%	0.1%
Direct Employment (% change 2008-2018)	-3.7%	-19.5%	-17.9%	-8.5%	-16.9%
Paper and Paper Products	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	0.55	2.9	2	7	0.5
Emissions (% Change 2008-2018)	15%	-6%	-54%	-14%	-45%
GVA (% of Economy) (2016)	0.36%	0.2%	0.2%	0.4%	0.3%
GVA as % of Economy (% Change 2008-2016)	-12.5%	-9%	15%	-9%	-11%
Direct Employment (% economy, 2016)	0.29%	0.2%	0.2%	0.3%	0.2%
Direct Employment (% change 2008-2016)	-20.5%	-23.2%	-17.8%	-10.2%	-10.8%
Food, Beverages && Tobacco	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	1.2	10.6	7.4	10.1	4.9
Emissions (% Change 2008-2018)	14%	-11%	-9%	-1%	2%
GVA (% of Economy) (2016)	2.65%	2.2%	1.6%	1.6%	2.4%
GVA as % of Economy (% Change 2008-2016)	1.9%	4%	-8%	4%	24%
Direct Employment (% economy, 2016)	2.44%	2.3%	1.3%	2.1%	1.5%
Direct Employment (% change 2008-2016)	-9%	0.3%	-3.2%	-5.2%	-0.3 %
Textiles	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	0.13	0.9	1.2	0.9	0.2
Emissions (% Change 2008-2018)	-7%	-33%	-40%	-24%	-25%
GVA (% of Economy) (2016)	0.56%	0. 3%	0.3%	0.3%	0.2%
GVA as % of Economy (% Change 2008-2016)	-36.1%	-22%	9%	-17%	-6%
Direct Employment (% economy, 2016)	0.7%	0.4%	0.3%	0.3%	0.2%
Direct Employment (% change 2008-2016)	-43.8%	-28.6%	-13.2%	-22.2%	-10.8%
Non-Metallic Minerals	**Flanders**	**FR**	**UK**	**DE**	**NL**
2018 Emissions (MtCO2-eq)	0.56	17.7	11.7	39	1.8
Emissions (% Change 2008-2018)	-25%	-30%	-28%	-3%	-23%
GVA (% of Economy) (2016)	0.6	0.4%	0.3%	0.6%	0.3%
GVA as % of Economy (% Change 2008-2016)	-16.5%	-21%	-1%	-3%	-24%
Direct Employment (% economy, 2016)	0.58%	0.4%	0.3%	0.6%	0.4%
Direct Employment (% change 2008-2016)	-13.5%	-21.1%	-29%	-11.2%	-27.8%

Table 9: Comparison of industrial emissions, GVA and employment Flanders and Neighbouring Countries

The above comparison table shows that Germany has the highest energy intensive industries (EII) emissions followed by France, the United Kingdom and The Netherlands. However, The Netherlands has the highest EII emissions as a percentage of economy-wide emissions (after Flanders).

The highest EII emissions reductions between 2008-2018 have come from the UK followed by France. Germany and The Netherlands saw relatively small decreases. The sectors with the highest emissions reductions has been the basic metals sector (UK), paper and paper products (UK), coke and refined petroleum (FR), chemical and chemical products (UK). In The Netherlands, emissions even grew in the food, beverages and tobacco products sector, the chemicals and chemical products sector, and the basic metals sector – the only country in the group to register a growth is emissions amongst the sectors presented above.

The significant decline in the UK and, to a lesser extent, France's EII emissions is related to major industrial closures that ensued over that period. Three large-scale UK refineries (Teesside (Petroplus), Coryton (Petroplus) and Milford Haven (Murco) closed in 2009, 2012, and 2014 respectively. There has also been a reduction of capacity through mothballing of primary distillation[264] while others have registered large losses which led to lower production.[265] Large integrated iron and steel plants in the UK closed in 2010 and 2015 (which included the second largest blast furnace in Europe) in addition to two of three aluminium smelters.[266] In France, there was a large industrial closure in steel production in 2011 (Florange). In Germany, a significant reduction took place in the chemical sector's non-CO_2 emissions, likely similar (catalytic) reduction measures that were taken a bit earlier in Flanders.

Flanders did not see industrial closures of large, single source emitters in the period 2008-2016. While there were important industrial closures in textiles, ceramics and automotive in that period in Flanders, these had a relatively limited impact on overall industrial GHG emissions. Out of all countries assessed here, the industrial emission profile of Flanders is most similar to the one presented for The Netherlands. This does not imply that the overall industrial profile itself is fully comparable between Flanders and The Netherlands.

EII GVA as a percentage of the economy is highest in Germany, followed by The Netherlands, the UK and France. EII GVA as a percentage of economy declined across all countries; however, the biggest loss between the period 2008-2016 was suffered by France (-6%), followed by Germany (-4%). In comparison, The Netherlands (-1%), and UK (-2%) suffered minor reductions. GVA as percent of economy fell most in the basic metals sector across all countries followed by the textiles wearing apparel, leather and related products sector (with the exception of the UK). In the coke and refined products sector, GVA as a percentage of economy fell sharply in the UK and The Netherlands but grew exponentially in Germany and France. However, there has been growth in GVA as a percentage of economy amongst all countries in the chemicals and chemical products sector with the exception of The Netherlands which registered a 5% decline.

Industry is a large employer in all countries compared. German industry direct employment as a percentage of total economy-wide employment is the highest followed by France, the UK and the Netherlands. Between, 2008-2018, the only sector to see positive growth in employment has been the food, beverages and tobacco products sector (2017 for DE, FR; 2018 for UK,

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[264] UK Department for Business, Energy & Industrial Strategy, 2017
[265] Critchlow, 2015
[266] Griffin et al., 2016

NL). Overall, all countries registered large losses between 2008-2016 in EII employment as a percentage of economy-wide employment.

10.3 International policy responses

Over the past few years, the EU and the four neighbouring countries of Flanders have launched a significant number of initiatives that attempt to facilitate industrial transition towards climate neutrality. First, national climate laws have since the Paris Climate Agreement emerged as new governance tools to help manage the low-carbon transition towards net-zero emissions.[267] All four of Flanders key neighbouring countries assessed in this report have adopted climate laws with long-term climate-neutrality targets. With the sole exception of France, the UK, The Netherlands, Germany and even the EU have developed industrial strategies in recent years. There also exist, in all four neighbouring countries, dedicated hydrogen strategies/initiatives/plans. Additionally, there are plans for infrastructure development and support for low-carbon technologies. Below, these key policy responses to the climate and industrial transition are enumerated and briefly assessed.

10.3.1 United Kingdom

10.3.1.1 Climate Law

The Climate Change Act in the UK, adopted in 2008, was the first of all climate laws that set a clear long-term direction whereas in the past, such framework laws saw short term targets and steady change. The UK climate change law works on the basis of emissions or carbon budgets (covering all GHGs) which ascertains allowable emissions in a five-year period, determined every 12 years prior to the debut of each period. The UK has also developed a number of sectoral roadmaps over the years.

Name: Climate Change Act 2008 (c 27)[268]
Adopted: November 2008
Major Revision: July 2019 (2050 Target Amendment) Order 2019 No. 1056)[269]
Long-term Target: -100% by 2050

10.3.1.2 UK Industrial Strategy: Building a Britain fit for the future[270]

Adopted in 2017, the UK's industrial strategy is a broad document which oversees a wide array of sectors under a "blended" approach which combines horizontal, sectoral and mission-based policies. Indeed, an Industrial Strategy Challenge Fund worth £4.7 billion to be spent over 4 years was set up as a core pillar and an independent Industrial Strategy

[267] Ecologique, 2020
[268] UK, 2008a
[269] UK, 2008b
[270] UK, 2017

Council was created to assess progress and make recommendations to the government. Moreover, the industrial strategy sees R&D investment raised to 2.4% of GDP by 2027 (including £12.5 billion more public R&D investment by 2021/22). Under the mission-based element of the strategy, four Grand Challenges are set out: artificial intelligence and data, ageing society, clean growth, and the future of mobility. Under the clean growth grand challenge, the UK aims to establish the world's first net-zero carbon industrial cluster by 2040 and at least 1 low-carbon cluster by 2030 (of the six large clusters mapped emitting 40 Mt CO_2 per year). It also seeks to develop roadmaps and feasibility studies for net zero industrial clusters, accelerate the development and deployment of low-carbon technologies and enable the deployment of infrastructure at scale by the mid-2020s while boosting the competitiveness of key industrial regions. The mission is backed by GBP 170 Mn public investment through the Industrial Strategy Challenge Fund matched by funding of up to GBP 261 Mn from industry.

10.3.1.3 UK Hydrogen Strategy

Although the UK does not have a hydrogen strategy, there have been significant key developments to that extent. While hydrogen for the transport sector has received ample attention (GBP 63 Mn in 2019[271]), industry has also been a core focus. In June 2019, the government awarded GBP 26 million to nine CCUS projects while in August 2019, GBP 390 Mn government funding was announced to help industry cut emissions including a GBP 40 Mn Hydrogen and Fuel Switching Innovation Fund, a new GBP 100 Mn competition to enable greater supply of low carbon hydrogen towards decarbonization and a new GBP 250 Mn Clean Steel Fund to support the iron and steel industry to transition to a low carbon future, including using hydrogen.[272] In 2020, there have been several calls, including by the Hydrogen Taskforce, for the government to develop a cross-departmental Hydrogen Strategy within the UK government.[273]

10.3.2 France

10.3.2.1 Climate Law

Adopted in mid 2015, France's energy transition green growth act is the country's climate law. Similar to the UK, France has also adopted a carbon emissions budget approach where the budget is set up to 10-15 years in advance.

Name: Energy Transition Green Growth Act (Loi de transition énergétique pour la croissance verte)[274]
Adopted: August 2015

[271] GBP 25 million investment to fund zero-emission transport innovations including feasibility of hydrogen fuel cell technology, GBP 33 million new investment towards the next generation of low-carbon vehicles, including to a hydrogen-powered engine project, and Five new Decarbonizing Transport Networks+ announced supported by GBP 5 million of funding from UK Research and Innovation, including one network for hydrogenfueled transportation.
[272] Baker McKenzie, 2020
[273] Gordon, 2020
[274] Legifrance, 2015

Major Revision: September 2019 (LAW n ° 2019-1147 of 8 November 2019 relating to energy and climate (LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte)[275]
Long-term Target: Carbon neutral by 2050 "factor of six reduction" by 2050 (>-83.3%)
Interim Target: -40% by 2030

10.3.2.2 France Hydrogen Strategy

In 2018, the French government announced its Hydrogen Deployment Plan for Energy Transition which includes EUR 100 Mn funding. It also includes targets for decarbonized / "green" hydrogen in industrial applications: 10% by 2023 and 20-40% by 2028, while increasing the number of hydrogen commercial and heavy vehicles and charging stations. The November 2019 amendment of the Energy-Climate law mentioned above also set targets for low carbon and renewable hydrogen to be 20% to 40% of total consumption of hydrogen and industrial hydrogen by 2030. Moreover, France's gas network operators have acknowledged that the country's gas network could be adapted to pipe a mix of natural gas with 10% hydrogen until 2030 and 20% hydrogen from 2030 onwards as part of a bid to cut carbon emissions.[276] Recently, as part of the COvid-19 recovery plan, France announced major investments in renewable hydrogen to the tune of EUR 7 billion for deployment of 6.5 G of electrolysers by 2030.[277]

10.3.3 The Netherlands

10.3.3.1 Climate Law

The Netherlands adopted a Climate Act on 2 July 2019, containing a framework for the development of a policy aimed at irreversible and stepwise reduction of Dutch GHG emissions in order to limit global warming and climate change. The Act introduces a CO_2 tax for large companies[278], limits CCS subsidies, increases tax for natural gas and surcharge for renewable energy for companies, transition to clean energy (including shutting down all coal plants), promotes use of blue and green hydrogen[279] and the acceleration of circularity amongst other sectorally-targeted elements. Specifically, the law sees the implementation of an ambitious EUR 2 Bn (upto 2030) innovation programme targeted at reducing costs for prominent low-carbon breakthrough technologies, a Stimulation of Sustainable Energy Production (SDE+) scheme, with an annual amount increasing to a maximum of EUR 550 Mn will become available by 2030 for carbon emissions reduction in industry (e.g. through the use of hydrogen or CCS), and additional funds to the tune of approximately EUR 40 Mn/yr to be made available from the Climate Budget for pilots and demo facilities.

[275] Legifrance, 2019
[276] Morgan. 2019
[277] De Beaupuy, 2020
[278] The carbon levy starting at EUR 30 per tonne CO2 in 2021 and going up to EUR 125–150 per tonne CO2 in 2030 including the ETS price will be target CO2 emissions in the industry sector by 14.3 Mt by 2030 compared to the baseline trajectory.
[279] The Climate Agreement sets the goal of realising 3 to 4 GW of electrolysis capacity in the Netherlands by 2030, allowing both green and (temporarily) blue hydrogen. In addition to the crucial private sector contribution, at least EUR 800 million in additional stimulus funds will become available for all types of hydrogen pilots and demo facilities over a period of ten years.

Name: Climate Act (Klimaatwet)[280]
Adopted: July 2019
Long-term Target: -95% by 2050
Interim Target: -49% by 2030

10.3.3.2Industrial Strategy

On May 2020, the the Dutch cabinet presented the ‘Vision on transition of basic industry for Netherlands’ as the counrty’s industrial strategy. The strategy has the ambition to transform The Netherlands into the (European) location for sustainable (basic) industry. With this strategy, the government seeks to support upscaling low-carbon pathways in new ways, focusing on a number of important technical developments: hydrogen, CCS, electrification and circular techniques, such as chemical recycling. The government also hopes to accelerate the development of certain low-carbon technologies. The strategy underlines that the infrastructure for the supply of sustainable energy and raw materials, heat and (residual) gases must be adapted to the needs of the industry in a climate-neutral future. With this vision, the cabinet outlines a new perspective for a sustainable, climate-neutral basic industry in the Netherlands.

10.3.3.3Hydrogen Strategy

The Dutch Government Strategy on Hydrogen, unveiled in March 2020, aims for the Netherlands to become a global leader in the production of hydrogen, a potential hub for providing hydrogen to neighbouring countries (especially Northwest European energy markets) and for Dutch companies to become key players in the development of regional and international hydrogen supply chains. Based on the strategy, a hydrogen programme is set to be jointly outlined and implemented with stakeholders. This includes the development of hydrogen infrastructure. The strtategy also sees a transition from blue to green hydrogen, the Porthos project in Rotterdam cited as a promising example of a blue hydrogen project.[281]

In order to facilitate a market for zero-carbon hydrogen, the strategy sees the need for a reliable system of Guarantees of Origin (GOs), seeking coordination with other European countries. More specifically, the strategy notes existing or planned support schemes for hydrogen production such as: the production of hydrogen by electrolysis to be included in the SDE++ for the first time, CCS will be able to compete in the SDE++ through the CCS category for the production of blue hydrogen, support for innovative pilots in the field of hydrogen through the DEI+ (Energy Innovation Demonstration Scheme), scoping study of hydrogen production from offshore wind energy via integrated tenders, and exploration of the introduction of an obligation for blending hydrogen in the natural gas grid (either physically or through certificates).[282]

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[280] Overheid.nl, 2019
[281] Government.nl, 2020
[282] Ibid.,

Northern Netherlands in particular hopes to be the leading hydrogen region in the country. Already in 2017, the "Northern Netherlands Innovation Board" (NIB) described its vision for a green hydrogen economy in the Northern Netherlands. In September 2019, the Northern Netherlands won EUR 20 million in EU funds to help it become the first "European Hydrogen Valley, matched by another EUR 70 million of public and private money. In May 2020, the Port of Rotterdam published its vision of becoming an international hydrogen hub. According to this vision, the port aims to have 2 GW of electrolysis capacity installed by 2020, producing hydrogen from offshore wind power from the North Sea.[283]

10.3.4 Germany

10.3.4.1 Climate Law

In December 2019, Germany's Climate Protection Law came into force, based similarly on the budget approach but with a slight variation. The law breaks down emissions pathway by each main economic sector with the possibility of short-term action plans for additional reductions where progress gaps are noticed. Regarding the industry sector, the law includes the following measures: gradual cut in electricity costs via reduction in the EEG (German renewable energy sources act) surcharge, a support programme for energy efficiency in the industry sector (including heating), a national decarbonisation programme which will support the development, demonstration and market introduction of innovative low-carbon production processes in the basic materials industries, funding for R&D in the field of CO_2 storage and use and dialogue with stakeholder groups for the same.

Name: Climate Protection Law (Klimaschutzgesetz)[284]
Adopted: December 2019
Long-term Target: GHG neutral by 2050
Interim Target: -55% by 2030

10.3.4.2 Industrial Strategy

In November 2019, the German "Industrial Strategy 2030 – Strategic Guidelines for German and European Industrial Policy"[285] was presented which foresees industry's share of GVA in Germany growing to 25%, support for SMEs, and the safeguard of prosperity and jobs of the future. The Industrial Strategy 2030 also envisages a variety of measures: improving the framework conditions for industry, measures to strengthen new technologies, and protecting Germany's technological autonomy in international competition. Regarding the long-term transformation of the industry sector towards climate neutrality, the strategy speaks about support for more R&D on low-emission technologies, scaling-up of hydrogen-based technologies, R&D for CCS and CCU technologies for industrial facilities, regional and European CCS/CCU infrastructure, further ways to use CO_2, and a reduction of costs. Regarding CO_2 storage, the strategy points toward large European offshore potential that will require

[283] Homan, 2019
[284] Bundesanzeiger, 2019
[285] Federal Ministry for Economic Affairs and Energy (BMWi), 2019

cooperation with Norway, the Netherlands and the United Kingdom in particular. The strategy also briefly mentions the relevance of lightweighting materials and calls for a strengthening of the bio-economy.

The German Economic Affairs Ministry has also established "Regulatory sandboxes for the energy transition"[286] as a new funding pillar in the 7th Energy Research Programme with the aim to try out technical and non-technical innovations on an industrial scale in key areas of the energy transition. Over a period of five years, the BMWi originally intended to fund the regulatory sandboxes with a total of EUR 100 million per year and – in addition – planned to provide a one-off sum of EUR 200 million for regulatory sandboxes in regions affected by structural change. H2Stahl, a project by thyssenkrupp Steel Europe which uses hydrogen in a blast furnace in Duisburg to replace coal injection reducing CO_2 emissions by about 20%, won support from this initative. Another recipient of such support is GreenHydroChem under which a 50 MW electrolyser at the Leuna chemical site will convert the electricity generated from renewable energy into hydrogen. Among other things, the hydrogen will be converted into chemical base materials and methanol in the local refineries.

10.3.4.3 National hydrogen strategy

According to the German national hydrogen strategy[287], published in June 2020, Germany plans to install 5 GW of electrolysis capacity by 2030, up to 10 GW by 2035 or 2040 at the latest, expand renewable energy capacity (especially offshore wind power) to account for the additional electricity demand for electrolysis, and exempt green hydrogen production from the renewables levy. The strategy refers to three existing funding programmes to support the switch towards hydrogen-based processes especially in the steel and chemical industry.[288] While blue and purple hydrogen may be used "in a transitional period", the strategy explicitly states that only green hydrogen shall receive specific public support. According to the strategy, a Contracts-for-Difference (CfD) instrument will be introduced to make up for the higher operating costs of hydrogen-based steel and chemicals production. The strategy expresses strong support for the implementation of a European IPCEI project on hydrogen and states German government intentions to intensify cooperation with other EU Member States, particularly in the North and Baltic Seas, but also in Southern Europe with a view to longer term need for hydrogen imports. In the same vein, Germany intends to integrate hydrogen in existing energy partnerships with other countries and pursue new partnerships with strategic export and import countries. Germany also plans to support the formation of a global hydrogen market, supported by a guarantee-of-origin instrument that can verify the sustainable production of imported hydrogen. More generally, the hydrogen strategy states the goal of German companies becoming important players on the global market for hydrogen and Power to X technologies.

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[286] Federal Ministry for Economic Affairs and Energy (BMWi), 2020a
[287] Federal Ministry for Economic Affairs and Energy (BMWi), 2020b
[288] "Decarbonisation in industry", "Hydrogen use in industrial production" and "CO_2 avoidance and use in basic industries"

One example of the momentum towards building a hydrogen economy in Germany is the GET H2 Initiative[289] which aims to establish the core for a nationwide hydrogen infrastructure and support the development of relevant technologies and their market launch through several projects. The partners of the initiative include among other companies Salzgitter, Air Liquide, RWE, BP, BASF, uniper and Siemens and also comprise of a number of research institutes.

Currently, the key project that the GET H2 initiative pursues is the Nucleus project, led by BP, Evonik, Nowega, OGE and RWE Generation, which links the production of green hydrogen with industrial customers in Lower Saxony and NRW. An approximately 130-kilometer network from Lingen to Gelsenkirchen is supposed to become the first hydrogen network in the regulated area with non-discriminatory access and transparent prices. The production of green hydrogen on an industrial scale and its supply to customers is scheduled to start at the end of 2022.

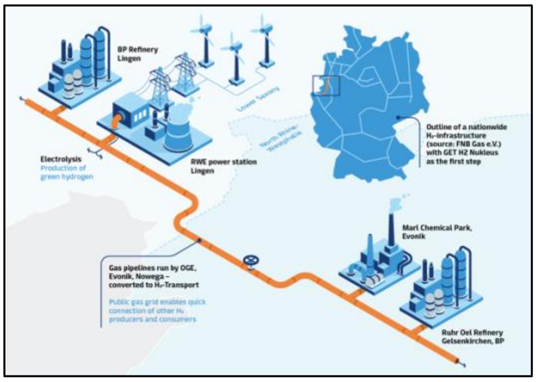

Figure 57: Schematic overview of the GET H2 Nucleus project (source: GETH2, n.d.b.,)

10.3.5 EU Level

10.3.5.1 Climate Law

At the EU level, a draft climate law, unveiled in Brussels on 4 March 2020, would make a legally binding commitment for the EU to reduce its GHG emissions to net zero by 2050. EU member states tentatively agreed in December 2019 to make the EU carbon-neutral by the middle of this century. The law would also give the European Commission the power to set binding short-term climate targets without unanimous approval from all 27 member states. Recently, in the 2020 State of the Union speech, the European Commission proposed an economy-wide reduction of 55% by 2030 compared to 1990 levels.[290] The law would enable the commission to adjust the EU's climate goals every five years, based on new scientific findings, emerging technologies and the state of the economy.

[289] GETH2, n.d.a.,
[290] European Commission, 2020e

10.3.5.2 EU Green Deal

The EU Green Deal,[291] – the proposed framework for the EU economy to achieve carbon neutrality by 2050 – will be the bloc's top priority. The green deal would unlock EUR 1 trillion (USD 1.1 trillion) over the next decade for climate action. A Just Transition Mechanism will also accompany the Green Deal in ensuring the transition to a carbon-neutral Europe by 2050 is both fair and balanced.[292] While the Green Deal is an ambitious initiative, its Sisyphean task will be ensuring the transition of European energy-intensive industries which are typically considered as 'hard to abate' sectors given their high CO_2-and-energy intensive processes and because most of the low-hanging fruits for decarbonisation have already been picked. The green deal is a credible first step. However, the transition to climate neutrality will also depend on the development of a comprehensive, integrated industrial strategy.

10.3.5.3 Industrial Strategy

In March 2020, the European Commission presented its new Industrial Strategy[293] that seeks to help deliver on three key priorities: maintaining European industry's global competitiveness and a level playing field, making Europe climate-neutral by 2050 and shaping Europe's digital future. The New Industrial Strategy sets out the key drivers of Europe's industrial transformation and proposes a comprehensive set of future actions, including:

- An Intellectual Property Action Plan to uphold technological sovereignty, promote global level playing field, better fight intellectual property theft and adapt the legal framework to the green and digital transitions.
- A review of EU competition rules, including the ongoing evaluation of merger control and fitness check of State aid guidelines, shall ensure that the EU's rules are fit for purpose for an economy that is changing fast, increasingly digital and must become greener and more circular.
- Comprehensive measures to modernise and decarbonise energy-intensive industries, support sustainable and smart mobility industries, to promote energy efficiency, strengthen current carbon leakage tools and secure a sufficient and constant supply of low-carbon energy at competitive prices.
- Measures to secure the supply of critical raw materials through an Action Plan on Critical Raw Materials and pharmaceuticals and by supporting the development of strategic digital infrastructures and key enabling technologies.
- A Clean Hydrogen Alliance to accelerate the decarbonisation of industry and maintain industrial leadership. The Alliance will build on existing work to identify technology needs, investment opportunities and regulatory barriers and enablers. (Future alliances should also include low-carbon industries, Industrial Clouds and Platforms and raw materials.)

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[291] European Commission, 2019b
[292] Khandekar, 2020
[293] European Commission, 2020b

- Further legislation and guidance on green public procurement.
- A renewed focus on innovation, investment and skills.

In addition to a comprehensive set of actions, both horizontal and for specific technologies, the Commission will systematically analyse the risks and needs of different industrial ecosystems through an inclusive and open Industrial Forum, to be set up by September 2020 consisting of representatives from industry, including SMEs, big companies, social partners, researchers, as well as Member States and EU institutions.

10.3.5.4 Hydrogen strategy

The European Commission has decided to adopt a new dedicated strategy on hydrogen[294] in Europe, with the aim to create an enabling environment to scale up clean hydrogen for a climate-neutral economy, boost investments into the supply, storage and transport of clean hydrogen, while also supporting the leadership of EU industry in this field. A comprehensive European approach shall enable clean hydrogen to already contribute to increased GHG emission savings by 2030 with a view to larger-scale deployment by 2050.

In the first phase (2020-24) the objective is to decarbonise existing hydrogen production for current uses such as the chemical sector, and promote it for new applications. It includes the installation of at least 6 Gigawatt of renewable hydrogen electrolysers in the EU by 2024 and the production of up to 1 Mt of renewable hydrogen. The second phase (2024-30) sees the installation at least 40 Gigawatt of renewable hydrogen electrolysers by 2030 and the production of up to 10 Mt of renewable hydrogen in the EU. In the third phase, from 2030 onwards and towards 2050, renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs.

Specifically, the strategy is expected to ascertain the role that clean hydrogen can play in the context of the green recovery and the growth strategy that is the Green Deal with the ambition of a climate-neutral Europe by 2050, identify the main barriers that currently prevent scaling-up the production and use of clean hydrogen, determine a set of actions to address those barriers and foster a competitive European value-chain and large scale production and use of clean hydrogen in a cost-effective way, taking into account the subsidiarity principle, and address the challenge of concomitant development of a well-functioning hydrogen market and a corresponding cost efficient EU infrastructure. Energy-intensive industries are expected to play a key role in developing a sizeable, well-functioning clean hydrogen market and a cost-effective infrastructure.

10.3.5.5 Hydrogen Alliance

Unveiled as part of the EU’s new industrial strategy, the European Commission will launch by mid-2020 an EU-wide “hydrogen alliance” to promote the production of clean hydrogen in an effort to speed up the

[294] European Commission, 2020c

decarbonization of industry. Modeled on the European Battery Alliance, which brought together more than 200 companies, national governments and research organizations, the Clean Hydrogen Alliance, will also bring together investors, governmental, institutional and industrial partners, building on existing work to identify technology needs, investment opportunities, and regulatory barriers and enablers.

10.3.5.6 Circular Economy Action Plan

In March 2020, the European Commission adopted a new Circular Economy Action Plan[295] – one of the main building blocks of the European Green Deal. With measures along the entire life cycle of products, the new Action Plan aims to make the European economy fit for a green future, strengthen its competitiveness while protecting the environment and give new rights to consumers. The new plan focuses on the design and production for a circular economy, with the aim to ensure that the resources used are kept in the EU economy for as long as possible. The Commission intends to develop the initiatives set out in the Action Plan with the close involvement of the business and stakeholder community.

10.3.5.7 EU long-term vision

In November 2018 the European Commission adopted its "Long-term vision for a prosperous, modern, competitive and climate neutral economy by 2050".[296] The vision intends to show how Europe can lead the way to climate neutrality by investing into technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for a just transition.

The Commission sees its vision to be in line with the Paris Agreement objective to keep temperature increase to well below 2°C, and to pursue efforts to keep it to 1.5°C. The purpose of this long-term vision is to create a sense of direction, and to inspire as well as enable stakeholders, researchers, entrepreneurs and citizens alike to develop new and innovative industries, businesses and associated jobs.

The long-term vision looks into the portfolio of options available for Member States, business and citizens, and how these can contribute to the modernisation of the European economy and improve the quality of life of Europeans. It seeks to ensure that this transition is socially fair and enhances the competitiveness of EU economy and industry on global markets, securing high quality jobs and sustainable growth in Europe, while also helping address other environmental challenges, such as air quality or biodiversity loss.

According to the vision, the road to a climate neutral economy would require joint action in the following seven strategic areas:

- energy efficiency
- deployment of renewables
- clean, safe and connected mobility

[295] European Commission, 2020d
[296] European Commission, 2018

- competitive industry and circular economy
- infrastructure and interconnections
- bio-economy and natural carbon sinks
- and carbon capture and storage to address remaining emissions.

As a background for the long-term vision several energy scenarios were developed based on the PRIMES model. The two scenarios that describe climate-neutrality by 2050 rely on a number of mitigation strategies in the industry sector, especially on direct electrification, the use of both hydrogen and synthetic fuels, an increase use of biomass and the application of CCS and CCU. In addition, one of these two scenarios (the 1.5LIFE scenario) also assumes that measures are taken to reduce demand for primary materials through improved material efficiency in manufacturing, higher recycling rates, material substitution and also end-use demand reductions.

	Baseline 2050	ELEC, H2, P2X, EE	CIRC	COMBO	1.5TECH	1.5LIFE	Mix95
GVA industry [bEUR13]	2665	2665	n.a.	2665	2665	n.a.	2665
% of 2015	*152%*	*152%*	*n.a.*	*152%*	*152%*	*n.a.*	*152%*
CO_2 emissions [$MtCO_2$]	484	205-231	192	176	29	53	62
reduction vs. 2015	*-36%*	*- 70%-73%*	*-75%*	*-77%*	*-96%*	*-93%*	*-92%*
CCS [$MtCO_2$]	0	57-61	44	60	80	71	46
Final energy [Mtoe]	253.5	215-254	222.2	230.7	222.2	196.5	232
reduction vs. 2015	*-11%*	*- 12%-25%*	*-22%*	*-19%*	*-22%*	*-31%*	*-28%**

Figure 58: Industry sector in 2050 in the EU long-term vision (source: Wachsmuth et al., 2019)

10.4 Neighbouring Industrial clusters connected to Flanders and cluster policies

10.4.1 Introduction

Industrial clusters are a concentration of industries in a particular geographical area. To achieve climate neutrality, targeting large industrial clusters offers the most potential. Sizeable industrial clusters allow the deployment of new infrastructure and investments in new innovative processes to take advantage of possible economies of scale like CCS, CO_2 transport, H2 production and transport. At the same time, as deeply integrated industrial clusters can also inhibit deep emission reductions[297], such strategic planning of infrastructure could lower transition risks and coordination costs compared to a scenario where individual companies and installations would need to plan their climate transitions individually. The largest industrial cluster in Europe lies in the North West of the continent and includes five countries: France, Belgium, The Netherlands, Germany and the UK.

[297] Janipour et al, 2020

While a comparison with industrial developments in neighbouring countries can give insights into the relative performance of industry in Flanders, it is also relevant to consider how some of the industrial clusters in neighbouring countries are linked to those in Flanders and each other. In particular the chemical and refining industry form part of a broader Northwest European cluster. In the Netherlands, three major industrial clusters are closely related to Flanders: the chemical cluster in Terneuzen/Zeeland, the chemical cluster around Maastricht/Geleen and the large industrial activities surrounding the port of Rotterdam. There are ethylene and propylene pipelines connecting Rotterdam, Antwerp and Terneuzen. An ethylene pipeline connection also exists between Antwerp and Geleen. In Germany, there is a large variety of industrial activity in Northrhein Westfalen (Ruhr), and connected by (ethylene) pipeline to Antwerp and next down to other industrial areas in Germany around Frankfurt and Ludwigshafen. In Belgium, there exists an ethylene/propylene pipeline connection from Antwerp to chemicals production in and around Feluy. In Northwest France, there's large industrial activity in Dunkirk (steel, pharma/chemicals) and around Lille.

10.4.1.1 The Northwest European Industrial Cluster

For the transition to climate neutrality, the required infrastructure and innovation is not sufficiently in place across the EU. New low-carbon processes will need new infrastructure for raw materials, energy and the realisation of more symbiosis between companies and sectors. In particular CCS (and to a lesser extent CCU) and processes using low-CO_2/H2 will require reliable transport and storage infrastructure. This means laying pipelines for the transport of CO_2 and hydrogen as well as providing reliable logistics chains that guarantee the supply of biomass and waste and materials to be recycled at a competitive price. Furthermore, higher levels of electrification might need strengthening of high voltage networks close to industrial consumers.

To assess the infrastructure needs and inform decisions that need to be made by policymakers, firm decision-makers and (public) financiers (such as the EIB), it would make sense to start working bottom up from medium and large industrial clusters present in Europe. The largest such industrial cluster in Europe lies between Northern France, Belgium, the Netherlands, Luxembourg and Western Germany and includes 20% of total European industrial sites, half of Europe's petrochemical production and about a quarter of the continent's primary steel production. 40% of the potential sites lie within a 200km radius. There are around 1,600 km of H2 pipeline present but most of this is located in the Netherlands and Belgium (850km) with smaller transport networks in Germany and France (390 and 303 km respectively). CO_2 pipeline networks in the EU are mostly absent and there is only limited transport of ammonia via pipelines.

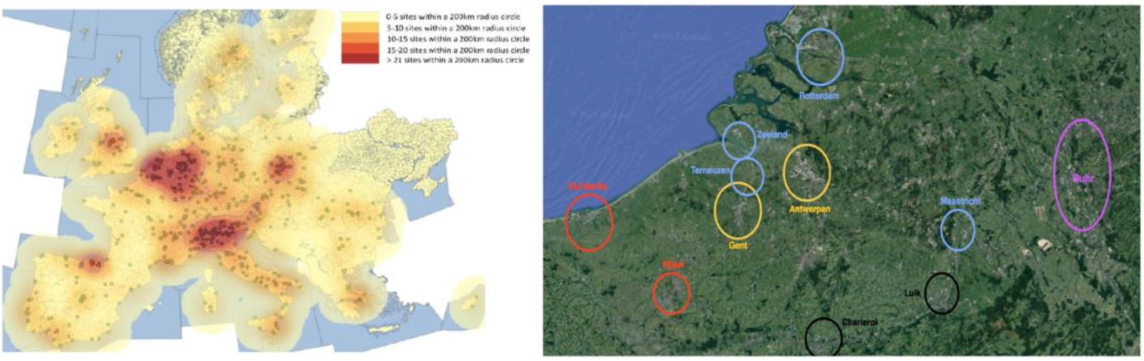

Figure 59: [Left] Concentration of industrial sites in Europe (Source: STRANE, 2016), [Right] Illustration of a selection of industrial clusters in and around Flanders (Source: Wyns et al., 2018b)

In particular, the region covering the triangle between Flanders, South Holland and the Rhine-Ruhr area is unique in Europe with regard to its density of heavy industry and its opportunities for companies to exchange mass goods between different sites via physical infrastructures. This is not only about the pipeline grid covering several different products but also about the Rhine river offering a very cheap transport option from the Amsterdam-Rotterdam-Antwerp (ARA) ports to Rhine-Ruhr and further up the Rhine to Ludwigshafen. Consequently, several petrochemical companies are running cross-border supply chains in the region, including the prominent examples of BASF (Antwerp and Ludwigshafen), INEOS (Antwerp and Rhine-Ruhr), Covestro/LANXESS (Antwerp and Rhine-Ruhr) and Shell (Rotterdam and Rhine-Ruhr).

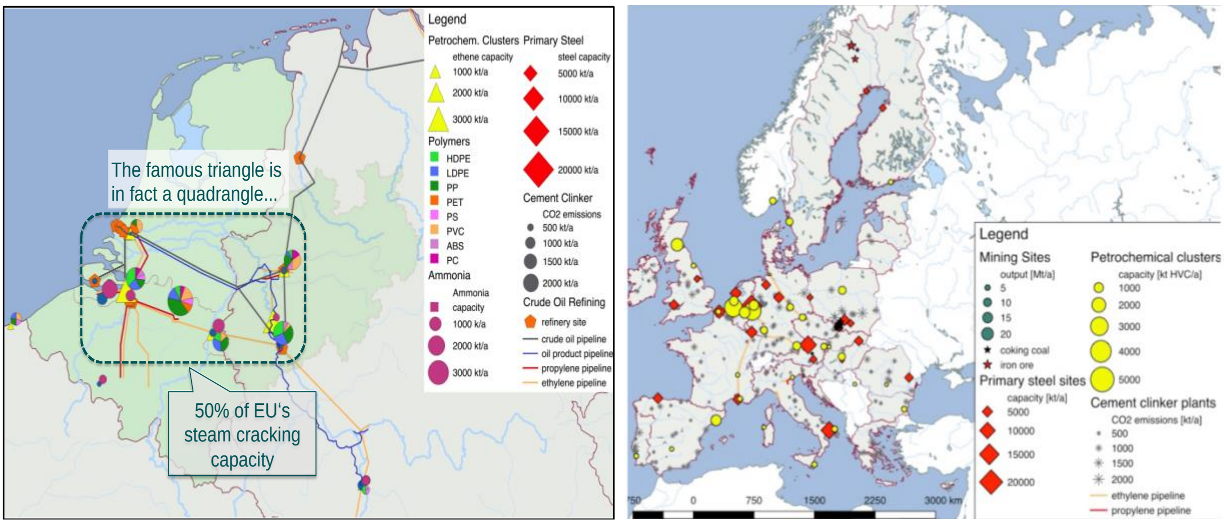

Figure 60: [Left] The petrochemical triangle (Source: Wuppertal Institute), [Right] Industrial sites in Europe (Source: WISEE Industry Stock database, Wuppertal Institute Presentation, 2020).

The pipeline grid for chemicals between Antwerp and Rotterdam provides the companies with flexibility in case of steam cracker outages but also enables a systematic exchange of ethylene and propylene, which is efficient due to the different demand structure in regard to the two major olefins at the two clusters.

In regard to the steel industry there is no such strong cross-border integration within the region. The planned ThyssenKrupp/Tata merger was an effort in such a direction, which so far has failed, however. The only steel producing company running cross-border chains in the region is ArcelorMittal. Its Ghent production site is integrated in a European wide production network including various sites in Luxembourg. ArcelorMittal's Duisburg site is very small and rather integrated in a local cross-company value chain than being cross-border integrated. But for the cheap import of raw materials to Duisburg, the Rhine link to Rotterdam is vital.

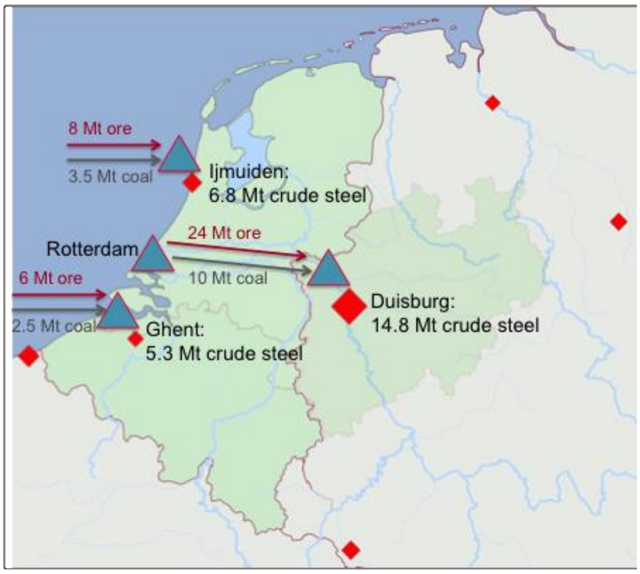

Figure 61: Primary steel plants and related flows in the ARA-Rhine-Ruhr region (source: Wuppertal Institute)

In regard to energy there is a strong integration between the Netherlands and Western Germany: Due to the gas fields in North Holland and the large-scale cavern gas storages in North Rhine-Westphalia there is a dense network of gas pipelines. With the upcoming closure of the gas fields and shrinking gas demand there are now redundancies in the gas pipeline grid offering the opportunity to convert existing pipelines to hydrogen pipelines. Another physical energy (and feedstock) infrastructure between ARA and Rhine-Ruhr are the pipelines for crude oil and oil products running from Rotterdam to Rhine-Ruhr. In the case of crude oil, Antwerp's refineries are also dependant to a significant extent on supplies from Rotterdam. On the contrary, the existing hydrogen pipelines between Rotterdam and Antwerp and also between the two clusters within the Rhine-Ruhr region (Cologne and Ruhr) with a capacity of 200 Nm^3 per year[298] each do not allow for a large-scale interchange that would be needed if hydrogen were to gain a major role in decarbonising heavy industry.

10.4.2 Cluster Mega Trends

Four mega trends are clearly visible in the Northwest European industrial cluster: strategic alignment, capture clusters, innovation, and infrastructure development. These are illustrated with the help of examples below.

[298] Own estimation by Wuppertal Institute based on the pipeline diameter and the reported pressure they are operated with.

10.4.2.1 Strategic Alignment

Trilateral strategy for the chemical industry
The trilateral region (Flanders, Netherlands and Nordrhein Westfalen) delivers 180 billion 20% of the European turnover in the chemicals sector.[299] It employs 350,000 people (11% of total EU chemicals sector employment). Finally, the trilateral region is one of the biggest R&D investors in the EU (EUR 38 Bn in 2015)[300].

In 2017 a trilateral strategy[301] for the chemicals industry was developed between the governments of Flanders, Netherlands and North Rhein Westphalia. This strategy has five overarching goals[302] for the regions to jointly become the global engine for a sustainable and competitive chemicals industry by 2030:

- Facilitating the transformation of the value chain to a digital, sustainable and circular chemicals industry.
- Increasing the quality and integration of the trilateral education and qualification systems towards the development of a regional labour-pool for a knowledge-based chemicals industry.
- Improving the weakened competitiveness with regard to energy costs of the trilateral region and ensuring a level playing field for the use of sustainable feedstock.
- Ensuring the development of critical infrastructure for the chemicals industry and making progress in developing a chemicals logistics 4.0 system.
- Improving the quality and effectiveness of policy coordination in the trilateral region with regard to issues of high cross-border priority for the chemicals industry.

Altogether, 21 measures in the three vertical policy fields (1) Research & Innovation, (2) Energy & Feedstocks, (3) Trilateral Chemical Infrastructure and one horizontal field (4) Policy Coordination, have been developed to augment the strengths of the trilateral chemical industry, capture the benefits of a growing chemical market and to remove existing bottlenecks for this development.

[299] Trilateral Chemical Region, n.d., Figures for 2015
[300] Vlaamse Regering, 2018
[301] https://www.wirtschaft.nrw/sites/default/files/asset/document/trilateral_strategy_chemical_industry.pdf
[302] Ibid

Research & Innovation	
N°	**Measures**
1	Improve the funding mechanisms for trilateral R&I actions
2	Intensify cross-regional R&D&I collaboration to improve the trilateral innovation ecosystem
3	Accompany a holistic digital trans-formation towards a 'New Verbund' based on value chain networks and virtual partnerships
4	Elaborate a trilateral scheme for demonstration plants
5	Expand the framework for start-ups and up-scaling in support of a trilateral chemical entrepreneurship ecosystem
6	Enhance the vocational training and lifelong learning systems for blue collar jobs to develop the chemical industry skills of the future
7	Encourage trilateral academic exchange and partnerships to improve the formation of the future academic workforce

Energy & Feedstocks	
N°	**Measures**
8	Develop a common trilateral approach for a competitive energy cost position
9	Form a level playing field for the use of sustainable feedstocks
10	Expand the trilateral availability of alternative feedstocks
11	Establish a circular ecosystem of integrated material and energy flows within and across industries
12	Enable comprehensive Circular Economy processes in the trilateral chemical industry

Chemical Industry Infrastructure	
N°	**Measures**
13	Develop a trilateral masterplan for chemical logistics and infrastructure
14	Accelerate approval processes of infrastructure and construction projects
15	Initiate a trilateral telematics system of transport and logistics undertakings
16	Establish a trilateral dialogue platform for Logistics 4.0
17	Plan and reserve space around chemical industry locations
18	Plan and reserve space for new pipelines

Policy Co-ordination	
19	Implement an institutionalised trilateral dialogue among policy makers, academia and industry
20	Trilateral positioning towards Europe in important policy fields
21	Decrease administrative requirements and barriers for trilateral co-operation

Figure 62: The 21 measures proposed in the trilateral strategy (source: MWIDE, 2017)

North Sea Port

Practical interregional cooperation already exists between industry in the Ghent harbour region and the Dutch Terneuzen area in the shape of the new Northsea Port venture. North Sea Port is the fusion of the Port of Ghent and Zeeland Seaports on 8th December 2017, which allowed it to become the third largest port in Europe (in value added) after the ports of Rotterdam and Antwerp. The merger strongly benefits both Flemish and Dutch economies by allowing the creation of a sustainable increase in employment, added value, transhipment (both maritime and inland), knowledge and resources and by fostering innovation. North Sea Port is now planning to further development of the multimodal infrastructure and further accessibility of the port as well as collaborate on sustainability. They actively work with all the partners involved in order to achieve their existing ambitious objectives in terms of sustainability more quickly.

Smart Delta Resources

The SDR platform is a collaborative initiative of eleven energy and feedstock intensive companies that constitute the industrial cluster of the Schelde Delta (a river delta in the Netherlands and Belgium) to reduce their use of energy and feedstock though industrial symbiosis. The industrial cluster includes 6 chemicals companies (Sabic, Yara, ICL-IP, Trinseo, Dow Benelux and Zeeland Refinery), 3 food companies (Cargill, LambWeston and Suiker Unie), 1 energy company (Engie Electrabel), and 1 steel company (Arcelor Mittal). In April 2018, SDR published a foresighting Roadmap: 'Roadmap towards a climate neutral industry in the Delta region' (SDR, 2018) which provides an ambitious yet feasible actionable plan for the industrial cluster through joint collaboration to reduce 85-95% emissions (or become climate neutral) by 2050 compared to 1990 (current emissions – 20 Mt CO_2). The companies themselves identified five methods to reduce GHG emissions from industrial processes: 1) Reduction of energy demand by application of new technologies, 2) Circular feedstock, 3) CO_2 capture usage and storage (CCU and CCS), 4) Climate-neutral energy carriers (H2 gas and electricity), and 5) CO_2-free energy sources, such as geothermic energy and renewable energy from solar or wind. From these methods, the roadmap developed eight concrete projects which maintain competitiveness and carbon neutrality (See section 10.1.3.4.)

10.4.2.2 Capture clusters → shared CO_2 transport and storage infrastructure

Carbon capture is a growingly key feature of the region's path to carbon neutrality. The region is well placed to take advantage of the benefits of CCS, given its ample CO_2 storage capacity, existing subsea infrastructure, and wide range of European industries that could decarbonise by capturing, using and/or storing their CO_2. Figure 63 below shows the approximation of EU emission clusters and storage locations, which would translate into relative ease of access for the Northwest European cluster's energy intensives to CO_2 storage With the increasing shift to a hydrogen economy, the industries of the cluster will also be able to take advantage of new and scale-able volumes of low-carbon hydrogen with CCS to enhance the efficiency, sustainability and cost effectiveness of production.

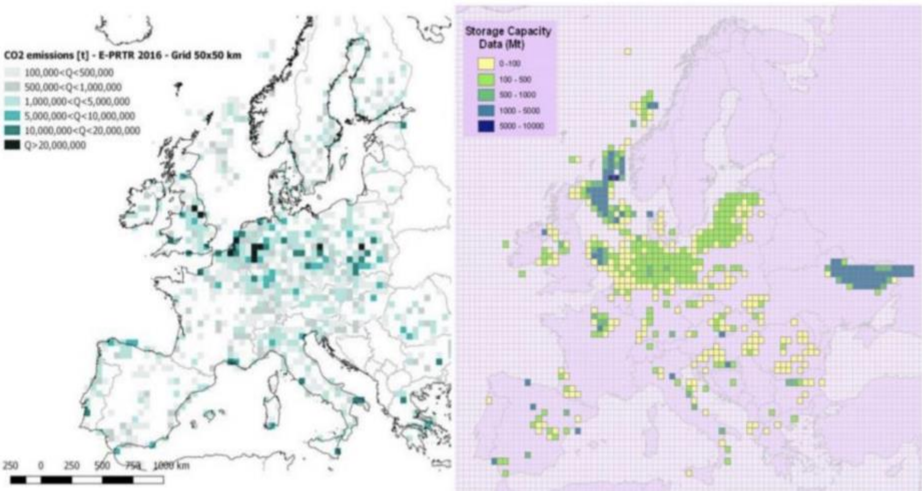

Figure 63: Comparison of CO_2 emission clusters and CO_2 storage capacity in Europe (Source: IOGP, 2019)

Developing the Northwest European cluster's CCUS potential would also allow for the creation of a larger regional CO_2 system that moves CO_2 clusters to offshore storage. One example is the interlinkage with the Northern Lights CCS project, part of the Norwegian government's ambition to develop a full-scale CCS value chain in Norway by 2024.

Figure 64: CCUS interlinkage between the Northwest and North European Industrial clusters (source: Equinor in IOGP, 2019)

Antwerp@C

The Port of Antwerp in Belgium is aiming to further reduce CO_2 emissions through carbon capture, utilization and storage (CCUS) infrastructure. Eight leading companies in the port area — Air Liquide, BASF, Borealis, Ineos, ExxonMobil, Fluxys, Port of Antwerp and Total — have signed a collaboration agreement to move toward the possible development of CCUS. The consortium is currently seeking financial from Flanders, the Belgian federal government and the EU. If the proposal turns out to be technically and economically feasible, development of such facilities could lead to significant reductions in CO_2 emissions in the run-up to 2030. A feasibility study will also investigate possibilities for CO_2 storage. Belgium does not have suitable geological formations for storing CO_2 underground, and so international collaboration would be needed.

Porthos CCS project

The Porthos project[303] is an initiative of EBN (a natural gas company owned by the Dutch government), Gasunie and the Port of Rotterdam Authority. The objective of the project is to achieve a generally accessible transport and storage infrastructure into which multiple parties can supply CO_2. The project organisation, Porthos, expects to be able to store 2 to 5 million tonnes of CO_2 per year in depleted offshore gas fields. In late 2019, Porthos signed an agreement with four companies to work in parallel over the

[303] Port of Rotterdam, 2019

following nine months on preparations for the capture, transport and storage of CO_2. These companies are ExxonMobil, Shell, Air Liquide and Air Products. The capture is to take place at these refineries and hydrogen producers in Rotterdam. According to planning, the first CO_2 will be stored beneath the North Sea by the end of 2023.

In February 2020 Porthos announced that the North Sea Port, the Port of Antwerp and the Port of Rotterdam Authority are jointly investigating how infrastructure between the ports could be developed to allow CO_2 from the North Sea Port and the Port of Antwerp to also use the Porthos CCS project. This „CO_2 TransPorts" project has received PCI status. This allows the three ports to apply for a subsidy from a European fund for infrastructure, the 'Connecting Europe Facility'. While the first phase of Porthos is expected to only involve CO_2 from companies in Rotterdam, the North Sea Port and the Port of Antwerp will be investigating the options of laying joint pipelines in their areas to which industry can connect. These local pipelines could then be connected with Rotterdam Porthos in a subsequent phase. As well as studying the feasibility, CO_2 TransPorts will also be investigating the timing and amount of CO_2 that can be stored.

Figure 65: Intended CO_2 pipeline of the Porthos project (Source: Port of Rotterdam, 2019)

10.4.2.3 Innovation

The Northwest European cluster is home to some of the most cutting-edge developments in breakthrough low-carbon technologies. Listed below are a few such examples of cooperative initiatives focused on innovation.

Cracker of the Future Consortium

One specific initiative being promoted by the Trilateral Strategy is the "Cracker of the Future Consortium".[304] In this consortium the six companies (BASF, Borealis, BP, LyondellBasell Industries, Sabic, and TotalSix) with petrochemical steam crackers in Europe jointly develop cracker technology that can replace gas-based furnaces with ones that use renewable electricity. A pilot low-carbon-footprint cracker is planned to be in operation by 2030 and widespread commercial-scale production is aimed for by 2050. The companies have signed an agreement to invest in R&D and share their knowledge.

[304] Scott, 2019

SPIN – Industrial Innovation Excellence Cluster
In November 2019, the Ruhr region "Industrial Innovation Excellence Cluster ", or SPIN ("Spitzencluster Industrielle Innovationen") was launched by the Ministry for Economic Affairs, Innovation, Digitalization and Energy of the State of North Rhine-Westphalia in cooperation with several companies, including Siemens, thyssenkrupp and Evonik. The cluster focuses on the development of technologies, processes and products for CO_2-neutral energy systems and the digital transformation in the field of industry. The state of North Rhine-Westphalia supports this new innovation platform with EUR 15 million. One of the initial SPIN projects is "P2X Herne", an open test platform for the development of Power-2-X technologies built on the site of the Herne combined heat and power plant. A Power-to-X plant built at the site could generate synthetic fuels or basic materials for the chemical industry.

VoltaChem
VoltaChem[305], "a business-driven Shared Innovation Program" connects the electricity sector, equipment sector, and the chemical industry. Its members include Vattenfall, Shell, Uniper and Aramco. The program aims for a joint development and implementation of new technologies and business models that focus on the use of renewable energy in the production of heat, hydrogen, and chemicals. VoltaChem focuses its developments in four technology program lines dedicated to specific technological niches:

- Power-2-Integrate: Technology scouting and developing economic, life-cycle & system models to better understand electrification opportunities and business cases.
- Power-2-Heat - Developing and testing flexible electrically driven heat production systems for high temperature processes.
- Power-2-Hdrogen: Developing and testing electrochemical production of green hydrogen and further conversion towards fuels and added value chemicals.
- Power-2-Chemicals: Developing electrosynthesis technology for selective oxidation of bio-based feedstock to chemical building blocks and direct conversion of CO_2 to commodity chemicals & fuels.

Several projects are currently running under the VoltaChem programme. Two examples are the following:

- H2020 SPIRE2 PERFORM - Platform Power: This project aims to construct a highly flexible pilot plant incorporating advanced integrated electrochemical technologies which allow for, among others, the valorization of biomass and efficient use of fluctuating electricity supplies in the production of performance materials.
- Paired Electrosynthesis of Specialty Chemicals: The main objective of the paired electrosynthesis project is to accelerate the development and implementation of industrial electrification. The focus is on technology development of electrochemical conversions where a valuable product is created both on the anode and cathode of an electrochemical cell. This increases overall system efficiency and lowers energy demand.

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[305] Voltachem, n.d.,

2 Seas

The 2 Seas Programme is a maritime cross-border Programme which covers the coastal regions along the Southern North Sea and the Channel area. Four different Member States are involved: England, France, the Netherlands and Belgium, and the total area represents a total of 88,000 square kilometres. This makes it one of the largest cross-border Programmes in Europe. The Programme is part-financed by the European Regional Development Fund and has a total of EUR 241 million ERDF to co-finance projects in the 2014-2020 period. The overall objective is to develop an innovative, knowledge and research based, sustainable and inclusive 2 Seas area, where natural resources are protected, and the green economy is promoted. The project provides a unique opportunity for this European region to become a world leader in one of the important solutions: conversion of CO_2 into useful products using renewable energy.

Electrons to High-Value Chemical Products - E2C

VoltaChem and partners from the 2 Seas region have joined forces in the interregional project "Electrons to high-value chemical products (E2C project)" which focuses on the conversion of CO_2 into chemicals and fuels, using renewable electricity. The aim of this expert consortium - consisting of 7 research partners and 35 industrial observer partners from the Netherlands, Belgium, France and England - is to accelerate the development and implementation of Power-to-X and CO_2 conversion technology. The project will run for 3.5 years and result in the construction and showcasing of two pilot installations demonstrating the possibilities of Power-to-X technologies.

10.4.2.4Energy, H2, and Infrastructure Development

Smart Delta Resources Platform Projects

- The SolventLoop project recycles expanded polystyrene (EPS) foam and recovers bromine. It is a large-scale chemical recycling of plastics in the region, which requires a long-term effort and investment of approximately EUR 140 million in a 250,000 tonnes waste plastics plant. Project partners are Dow, Trinseo and Zeeland Refinery, as potential clients of such a plant. North Sea Port will be involved as port authority.This plan requires the development of a logistic chain and a pyrolysis plant, supplying the SDR companies Trinseo and Dow with circular feedstock. It is foreseen that products of the pyrolysis plant may need pre-processing in terms of hydro-treating and/or hydrocracking, before the product can be used as a feedstock. This may imply a new future-proof activity to Zeeland Refinery.
- ‘Circular feedstock supply’ project seeks to construct, by 2030, a regional circular plastics plant (pyrolysis unit with a capacity of 250,000 tonnes of mixed waste plastic) to create recycled plastics feedstock for plastics, as well as a network of pyrolysis units for waste plastics or polystyrene over the whole of north western Europe producing a naphtha-like pyrolysis oil suitable for the production of PE and PP or PS. The project would cost around EUR 150 Mn.
- The main objective of the ‘Regional CO_2 network’ project is the creation of a CO_2 network connecting CO_2 sources in the Delta region

to a network for storage (CCS) and/or to users of CO_2 (CCU). Given the absence of suitable storage options in the Delta region, one option could be the development of infrastructure (pipelines and storage facilities) as exist in Rotterdam for example. The project would cost around EUR 120 Mn.

- With the help of heat pump technologies, the ‘Stimulation of heat-pump technology at SDR companies’ project seeks, by 2030, to reduce 20% of the current energy used for heat supply at SDR companies resulting in a reduction of energy costs and mitigation of around 1,600 thousand tonnes GHG emissions. The ‘Geothermic potential in Bergen op Zoom’ plant project, operational by 2035 in the Bergen op Zoom Region, will supply carbon-free geothermic heat of 110-180ÅãC to SDR companies in the western Brabant region most of whom require less high temperatures than the chemical industry. The project would cost between EUR 2-12 Mn.
- The ‘Steel2Chemicals’ project is under preparation will see ArcelorMittal deliver its residual gases to Dow Benelux allowing ArcelorMittal to reduce its emission of CO and CO_2 and Dow Benelux to not only becomes less dependent on oil but also avoid the need to build feedstock production infrastructure for its plastics production. The project would cost around EUR 300 Mn.
- The ‘Robust and cost-effective electricity network infrastructure’ project seeks to ensure a robust and cost effective electricity network via access to wind energy (inclusion in the regional highvoltage grid), large-scale electrification in industry (power2heat, power2products, etc) and developments of the existing power generation in the region (e.g. Doel and Borssele) as well as onsite gas-fired CHP units.
- The ‘Power2Hydrogen’ project will create a regional facility that provides clean H2 produced from renewable energy (range of 10-20 MW) by means of a H2 network in the SDR region by 2025 addressing the existing gap between the size of the current electrolysis plants (6-12 MW, i.e. 300-720 ton H2) and the amount of H2 consumed in the region (about 405,000 ton H2). The project would cost around EUR 40-70 Mn.
- The ‘Region H2 open network infrastructure’ project consists of an open infrastructure H2 network (like the current natural gas network) connecting H2 and oxygen production capacity to the major H2 and oxygen users in the Delta region by 2030. This carbon-free H2 used by SDR companies as a feedstock and an energy source replacing natural gas would potentially mitigate 3.1-5 Mt CO_2 emissions per year. The project would cost around EUR 70 Mn.

Green Octopus

The project’s purposes are to boost the development of offshore wind power in Europe and to create a hydrogen infrastructure to connect North Sea ports with industrial clusters in France, Belgium, the Netherlands and Germany. To this end, the project plans to convert natural gas pipelines to hydrogen pipelines. The companies involved in this proposed project include energy company Engie, the Dutch natural gas infrastructure and transportation company Gasunie, the German steelmaker Salzgitter and the Port of Antwerp.

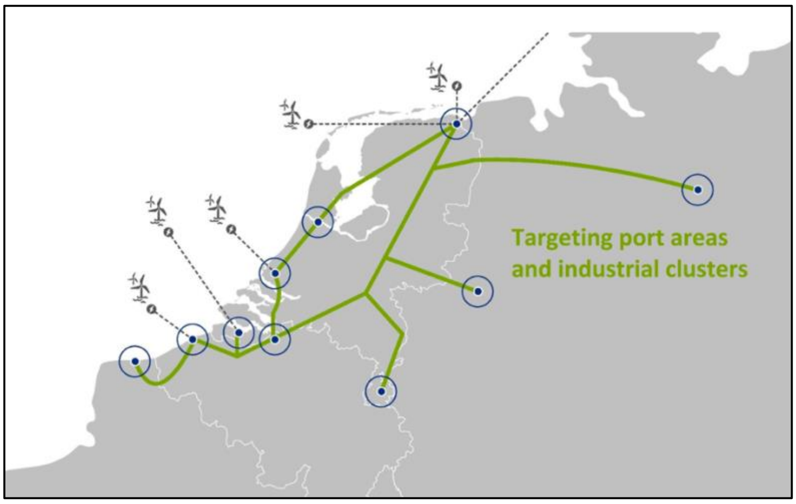

Figure 66: Schematic overview of the proposed Green Octopus project (source: Waterstofnet, 2019)

Silver Frog

The Silver Frog project[306] proposes the construction of manufacturing facilities for cutting-edge solar PV and water electrolysis technologies of a 2 GW solar module factory which will be used to help deploy 10 GW of renewable energy generation capacity – including wind power – to provide the electricity to produce 100% green hydrogen. The hydrogen will be transported using gas pipelines to help decarbonize heavy industries such as chemicals and steelmaking. The companies behind this project include the Swiss mechanical engineering company Meyer Burger, the Belgian-based unit of Canadian hydrogen business Hydrogenics, the Hungarian PV module manufacturer Ecosolifer and the Danish renewables developer European Energy. Project partners intend to produce around 800,000 tons of green hydrogen over eight years.

Hy3 and RH2INE

The Hy3 project[307] was initiated in January 2020. It investigates the potential for green hydrogen business models between the Netherlands and North Rhine-Westphalia. The focus is on the production of green hydrogen by offshore wind turbines, which can be transported to major industrial customers in North Rhine-Westphalia through converted natural gas pipelines. The Hy3 feasibility study will be completed by the end of 2020.

Another project that was initiated in January 2020 was the RH2INE (Rhine Hydrogen Integration Network of Excellence) project[308]. Together with the province of South Holland and the ports of Rotterdam, Duisburg, Neuss/Düsseldorf and Cologne, the state of North Rhine-Westphalia wants to work with RH2INE on the development of an infrastructure for hydrogen supply in the Rhine ports. The aim is to ensure this by 2030 for freight transport, especially inland waterway transport along the Rhine-Alpine corridor (Rotterdam-Genoa). In a first project, a feasibility study on the use of hydrogen in inland waterway transport and port infrastructure will be

[306] Hydrogen for Climate Action, 2019
[307] Energieagentur, 2020
[308] Idid.,

carried out. Further projects will identify synergies with other sectors, especially industry.

10.5 Roadmaps and studies

This section assesses in detail a large selection of the most pertinent European roadmaps and studies on the decarbonization of the industrial sectors. For the purpose of this study, roadmaps are understood as those which have modelled decarbonization scenarios. An overview of the roadmaps is provided before each sector subsection while individual summaries of the roadmaps and studies are provided in Annex 1. Relevance and key takeaways of the assessment of the roadmaps and studies for Flanders are provided for each sector below.

In general, the roadmaps considered in this study show that across a range of industries (steel, chemicals, refining and paper) but also across multiple industrial sectors in a country (Netherlands) or region (Port of Rotterdam) in theory deep emission reductions are possible but challenging. Only in recent years, the case is being made of the possibility of mitigation of upto 100% compared to different historical baselines. In most cases, the deep emission reductions depend on breakthrough technologies that still need to be proven commercially (e.g. CC(U)S and H2 based feedstock/synthetic fuels). In all cases deeper mitigation will require high levels of CAPEX (e.g. EUR 55 Bn for McKinsey & Co 20014 scenario to reduce emissions in Dutch industry by 80% in 2040).

Often the OPEX of the new technologies is higher compared to those currently used. It is also clear that a mix of different technologies will have to applied within and across industrial sectors. The specific mix of technologies will likely depend on local circumstances (e.g. the availability of pure CO_2 streams and storage locations, affordable and reliable biomass and/or H2 (via renewable electricity), waste streams from one sector as input for another production process, etc.). It is highly likely, when looking at the roadmaps and the modelled technologies that electricity demand will rise significantly in most decarbonisation scenarios bringing extra challenges to the energy system.

For Flanders, this implies that all the technological options and scenarios presented in the roadmaps will have to be applied and calibrated to the specific regional context (e.g. availability of affordable biomass and H2, electricity demand). The roadmaps and studies considered in this report are useful in the sense that they look at the bigger picture and international context important for competitiveness. They offer interesting but limited insights into the specific decarbonisation options for Flanders.

10.5.1 Chemicals Roadmaps

A list of the roadmaps and studies assessed for the Chemicals sector is provided below.

CHEMICALS SECTOR					
	Published	Name	Author:	Scope:	Decarbonsation Scenarios
Roadmaps	2013	European Chemistry for growth, unlocking a competitive, low carbon and energy efficient future	ECOFYS & CEFIC	EU 1990-2050	40%, 80%, 80% 50%
	2014	Europe's low-carbon transition: understanding the challenges and opportunities for the chemical sector	ECF & McKinsey	EU NA-2030	50 to -75% of scope 1 and 2
	2014	Energy transition - mission (im)possible for industry	McKinsey & Company	Dutch industrial sector 1990-2050	40% by 2030, 60% by 2040, 80% by 2040, 95% by 2050
	2016	Decarbonization pathways for the industrial cluster of the Port of Rotterdam	WI & Port of Rotterdam	Industrial Cluster Port of Rotterdam - 1990-2050	30%, 75%, 98%, 98%, 98%
	2017	Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry	JRC EC	EU 2013-2050	36%, 36.8%
	2017	Low carbon energy and feedstock for the European chemical industry	DECHEMA	EU 2015-2050	117 MtCO2, 216 MtCO2, 498 MtCO2
	2017	Taking the EU chemicals industry into the circular economy	ACCENTURE	EU NA-2030	12 Mt, 17 Mt, 19 Mt, 8 Mt, 10 Mt looped chemicals
	2017	Energy Technology Perspectives	IEA	Global (here: Chemicals & Petrochemicals)-2014-2060	975 Mt CO2/year, 321 Mt CO2/year
	2018	Roadmap for the Dutch Chemical Industry towards 2050	ECOFYS & Berenschot	Netherlands 1990-2050	80-95%
	2019	Working towards a greenhouse gas neutral chemical industry in Germany	VCI	Germany (6 chemicals) 1990-2050	80%, 95%, 100%
	2019	Climate-Neutral Industry: Key Technologies and Policy Options for Steel, Chemicals and Cement	Agora Energiewende,Wuppertal Institute	Germany 1990-2050	51%, 95%
	2019	Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry	Material Economics	EU 2015-2050	100%
Studies	2015	Evolution of competitiveness in the European chemical industry: historical trends and future prospects	Cefic & Oxford Economics	EU	
	2015	Fertilizers and Climate Change, Looking to the 2050	Ecofys	European fetilizers sector	
	2017	Fertilizers and Climate Change, Looking to the 2050	VCI	German Chemical Industry Association	

	2017	Joint Industry - Government Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan	UK Department for Business, Energy and Industrial Strategy (2017)	UK Chemicals Sector	
	2018	Filling gaps in the policy package to decarbonise production and use of materials	Climate Strategies and DIW Berlin	EU Basic Materials (here: Checicals)	
	2018	Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe	Wyns et al.,	EU Energy Intensive Industries	
	2019	Industrial Transformation 2050 –Towards an Industrial Strategy for a Climate Neutral	Wyns et al.,	EU Energy Intensive Industries	

Table 10: List of chemical sector roadmaps and studies assessed.

Below - Table 11: Overview of chemical sector roadmaps

Name	European Chemistry for growth, unlocking a competitive, low carbon and energy efficient future	Europe's low-carbon transition: understanding the challenges and opportunities for the chemical sector	Decarbonization pathways for the industrial cluster of the Port of Rotterdam	Energy transition - mission (im)possible for industry	Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry	Low carbon energy and feedstock for the European chemical industry	Taking the EU chemicals industry into the circular economy	Energy Technology Perspectives	Roadmap for the Dutch Chemical Industry towards 2050	Working towards a greenhouse gas neutral chemical industry in Germany	Climate-Neutral Industry: Key Technologies and Policy Options for Steel, Chemicals and Cement	Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry
Published:	2013	2014	2016	2017	2017	2017	2017	2017	2018	2019	2019	2019
Author:	ECOFYS & CEFIC	ECF & McKinsey	WI & Port of Antwerp Rotterdam	McKinsey & Company	JRC EC	DECHEMA	ACCENTURE	IEA	ECOFYS & Berenschot	VCI	Agora Energiewende,Wuppertal Institute	Material Economics
Scope:	EU 1990-2050	EU NA-2030	Industrial Cluster Port of Rotterdam - 1990-2050	Dutch industrial sector 1990-2050	EU 2013-2050	EU 2015-2050	EU NA-2030	Global (here: Chemicals & Petrochemicals)-2014-2060	Netherlands 1990-2050	Germany (6 chemicals) 1990-2050	Germany 1990-2050	EU 2015-2050
	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios	Scenarios
Scenario 1	**Continued Fragmentation Scenario** **Mitigation**: -40%	**Abatement category 1: Raw materials** **Mitigation**: - LCA of 5 chemical products: -50 to -75% of scope 1 and 2 emissions. Additional Scope 3 reductions: > 90 MtCO_2e	**Business As Usual** **Mitigation**: -30%	**Reference Scenario** **Mitigation**: -40% by 2030	**Baseline scenario** **Mitigation**: -36%	**Business as Usual** **Mitigation**: +119 MtCO_2 **Investments**: €2,1 Bn/annum	**Substituting raw materials** **Mitigation**: 12 Mt looped chemicals **CAPEX**: €20-40 Bn	**Reference Technology Scenario (RTS)** **Investments**: USD 6.8-8.0 Tn (2017-2060)	**2030 compliance at least cost** **Mitigation**: -80-95% **Investments**: €16 Bn in and €25 outside chemical industry (up to 2050)	**Reference Pathway** **Mitigation**: -27% (812.1MtCO_2) (80% since 1990) **Costs**: 54TWh electricity/y required **Investments**: Current level of €7 Bn/y	**2030** **Mitigation**: -51% (56 MtCO_2 from 2018) **Investments**: 59% reinvestment	**New Process Pathways** **Mitigation**: -100% (173 MtCO_2 from 2015) **Investment** in plastics production capacity/y: 199%
Scenario 2	**Isolated Europe Scenario** **Mitigation**: -80%	**Abatement category 2: Chemical Production**	**Technological Process** **Mitigation**: -75%	**Cheaper route** **Mitigation**: -60% or 20 Mt CO_2 by 2040 **Cost**: electricity demand ↑ 215 PJ (renewable ↑64 GW, cost @ EUR 21-23 Bn) **Investments**; 80%	**Fuel price variations (AS1)** **Mitigation**: - Similar to baseline scenario	**Intermediate** **Mitigation**: -117 MtCO_2 (incl. savings from synthetic fuels production) **Investments**: €17,0 Bn + €14,1 Bn (for efficiency measures p/a)	**Increased re-use of end-user products** **Mitigation**: 17 Mt looped chemicals	**2DS** **Mitigation**: -975 Mt CO_2/year (30% of current levels). **Investments**: USD 6.3-7.3 Tn (2017-2060) (30% for chemicals and petrochemicals)	**Direct actions and high-value applications** **Mitigation**: -80-95% **Investments**: €27 Bn in, €37 outside chemical industry→ 2050	**Technology Pathway** **Mitigation**: -61% (44.4 MtCO_2) (95% since 1990) **Costs**: 224 TWh electricity/y 2040 o/w **Investments**: €15 Bn additional	**2050** **Mitigation**: -95% (192 MtCO_2 from 2018)	**Circular Economy Pathway** **Mitigation**: -100% (173 MtCO_2 from 2015) **Investment** in plastics production capacity/y: 158%
Scenario 3	**Differentiated Global Action Scenario** **Mitigation**: -80%	**Abatement category 3: End-product Usage**	**Biomass and CCS (BIO)** **Mitigation**: -98%	**Steeper route** **Mitigation**: -80% or 36 Mt CO_2 by 2040 **Cost**: EUR 55 Bn, energy demand (including feedstock)- -17% by 2050	**CO2 price variations (AS2)** **Mitigation**: - Similar to baseline; most favourable scenario: -36.8%	**Ambitious** **Mitigation**: -216 MtCO_2 (incl. savings from synthetic fuels production) **Investments**: €19,2 Bn + €14,1 Bn (for efficiency measures p/a)	**Mechanical recycling** **Mitigation**: 19 Mt looped chemicals **CAPEX**: €10-20 Bn	**B2DS** **Mitigation**: -321 Mt CO_2/year (30% of current levels) **Investments**: USD 7.0-8.7 Tn (2017-2060)		**Greenhouse Gas Neutrality Pathway** **Mitigation**: -100% **Costs**: 628 TWh electricity/y mid-2030 o/w **Investments**: €45 Bn additional		**Carbon Capture Pathway** **Mitigation**: -100% (173 MtCO_2 from 2015) **Investment** in plastics production capacity/y: 122%
Scenario 4	**Level Playing Field Scenario** **Mitigation**: -50%	**Abatement category 4: End of Life**	**Closed Carbon Cycle (CYC)** **Mitigation**: -98%	**Steeper route** **Mitigation**: -95% or 46 Mt CO_2 by 2050 **Cost**: EUR 71 Bn until 2050		**Maximum** **Mitigation**: --498 MtCO_2 (incl. savings from synthetic fuels production) **Investments**: €26,7 Bn+ €14,1 Bn (for efficiency measures) p/a	**Chemical recycling** **Mitigation**: 8 Mt looped chemicals **CAPEX**: €30-80 Bn					
Scenario 5			**Closed Carbon Cycle Earlier Closure (CYC-ECE)** **Mitigation**: -98%				**Energy recovery and carbon utilization** **Mitigation**: 10 Mt looped chemicals **CAPEX**: €100-140 Bn					

Technology Portfolio (included in roadmap and irrespective of scenarios)	Bio-based feedstock, Valorisation of waste & recycling of plastics CCU/CCS, Greater process energy efficiency, Heat recovery and reuse, Renewable energy and CHP, End of pipe emission abatement, Measures that reduce emissions in nitric acid production, Mitigation options for ammonia, cracker products and chlorine	Mature tech implementable in near to medium term, Circularity, Renewable feedstock, Shift to green energy, CCS	**TP Scenario** BAT implementation, Renewable electricity for heat and H2, Energy efficiency, CCS. **BIO Scenario** Major technological breakthroughs esp. CCS, CO2 grids and storage sites, CO2 pilot grids by 2020. **CYC Sscenario** Methanol-based feedstock, Fischer-Tropsch wax, Energy efficiency improvements both in processes and in cross sectional strategies, Renewable energy as a fuel or heat source, Electrification, Change in feedstock from mineral oil to natural gas and carbon feedstock, Industrial symbiosis, CCS/CCU. **Demand side reduction measures** Offshore wind, Bio-based chemistry, Demand-side-management and energy storage, CO2 transport and storage, Synthetic fuels, Carbon-neutral primary steel.	Energy efficiency, Electrification of heat demand, Change of feedstock, Develop routes to reuse and recycle materials, Decide on steel production route(s), Develop CCS/U	**For energy:** 16% of saving attributed to savings in feedstock, 84% savings from electricity or fuels (thermal needs or steam processes). **For soda ash:** most important BAT = integrated design and operation. **For ethylene oxide/monoethylene glycol:** adoption of OMEGA technology, further CHP, CCS. CCS	Energy efficiency, H2 & CO2-based production routes, Biomass & biomass waste streams to chemicals, Electricity-based processes, Industrial symbiosis & circular economy, CCS	Biomass, New re-use "as is" products and solutions, Mechanically recycled molecules, Reverse logistics capabilities, Processing partnerships, Cracking and gasification processes, Molecular energy recovery, Capture and reconstruction of new chemical feedstocks	**B2DS Scenario** Energy efficiency and BAT deployment (42%), innovative processes and CCS (37%), Lower carbon fuels and feedstocks (13%), Material efficiency strategies (8%).	Circularity, Alternative feedstock, Energy efficiency, Renewable energy, CCS, Sustainable product	**Electricity-Based Processes** Methanol from electrolytic hydrogen and CO2, Ammonia and urea from electrolytic H2 and CO2, Electrically heated cracking, Electrically heated steam reforming, Synthetic naphtha/methane from electrolytic H2 and CO2. **Alternative Raw Materials/Processes** Chemical recycling of plastics (pyrolysis, gasification, depolymerization), Thermo-catalytic biomass conversion into BTX, Synthetic naphtha/methane from biomass, Co-firing with biomass, Methane pyrolysis. **Downstream Processes** Ethylene/propylene via methanol-to-olefins (MtO), BTX via methanol-to-aromatics (MtA), Olefins from synthetic naphtha and cracking, Olefins from synthetic methane + oxidative coupling of methane.	Heat and steam generation from power-to-heat from 2020, CO_2 capture at combined heat and power plants 2035 – 2045, Green hydrogen from renewable energies 2025 – 2035, Methanol-to-olefin/-aromatics-route 2025– 2030, Chemical recycling 2025 – 2030, Electric steam crackers 2035 – 2045	**Clean Up Current Processes** Increase process-& energy-efficiency (steam crackers), Switch to lower-CO2 fuels and electricity, Increased use of lighter feedstock **New Processes & Feedstocks** Plastics from bio-feedstock, Chemicals recycling of end-of-life plastics (depolymerisation, solvolysis, pyrolysis + steam cracking, gasification), Reprocessing of by-products (e.g., through methanol-to-olefins), New polymers and catalysts. **Electrification** Electrification of steam crackers, Electrification of cooling, heating, compression, and steam, Electrification of hydrogen production. **Carbon Capture** CCS on steam cracker furnaces and refinery processes, on waste-to-energy plants, 'Synthetic chemistry' ('power to X').
Assumptions	Competitiveness, Energy price, Impact on production CO2 price, Feedstock prices, Value chain integration.	All today's emissions covered by ETS, Net costs after 2020 depend on 2030 EU climate package Recycling rte ↑ 85-95% in production waste & 5% in construction waste, Impact on competitiveness assessed, assuming implementation in the near term.	**BIO Scenario**: energy-related emissions near-zero by 2050, electrified heat and mechanical energy, remaining thermal power plants connect to CO2 grid instead of using fossil fuels, strong Carbon Tax. **CYC**: closure of coal-fired plants by 2025, CCS economically unviable, sustainable biomass sourcing unnecessary.	Demand side measures focus strongly on circular economy (reuse, remanufacturing and recycling) influenced by the 'Nederland circulair in 2050'.	European industry remains globally competitive and demand is met with production An increase by 45.6 % of the demand in the Baseline Scenario In BS: prices for CO2.eq allowances, fuels and feedstocks follow the assumptions of the 2013 EU Energy and GHG emissions reference scenario (EC, 2013).	Increased demand for low carbon power Increased demand for CO2 as feedstock Increased demand for biomass as feedstock Extensive additional investments 1 % growth per annum for the EU chemical industry In BAU scenario: the power sector does not show further progress in decarbonization.	Lesser production of virgin chemicals would save around 250 TWh of energy.	Decreased demand in both 2DS and B2DS is -4% (17.8 EJ) or 1.3 GtCO2 cumulative savings compared with the RTS achieved through material efficiency, improving collection and processing rates of plastic-based consumer products which means less ammonia (70 Mt), methanol (68 Mt), and HVC (1,292 Mt).	Energy efficiency improves at 1.0%/year after 2005, Continued added value growth of 1% /y.	Electricity cost assumption: EUR 0.04/kWh including levies and taxes, To achieve GHG neutrality, the annual electricity requirements of the chemical industry would increase to more than eleven times (628 TWh) the current amount (54 TWh).	Long-term, cross-party assurance that Germany will ensure internationally competitive energy prices new version of the EU state aid guidelines must be geared towards climate neutrality.	Production increase of 15%, from 62 Mt in 2015 to 71 Mt per year in 2050, emissions rise from 173 MtCO2 in 2015 to 192 MtCO2 in 2050.

Key Takeaways for Flanders

The chemical roadmaps and studies tend to focus on high value chemicals and ammonia which are extremely relevant for Flanders. Most of them conclude that Net-0 or close to Net-0 emissions are theoretically possible. To achieve this, a large proportion of the roadmaps assume CCUS, high use of H2 and/or high use of biomass as the main routes. However, and more recently, circular economy and in particular circular plastics (Accenture, 2017; Material Economics, 2019) have become important pathways in these roadmaps and studies, in many cases, an essential component to achieve climate neutrality while keeping the use of other feedstocks or renewable feedstocks under control. In particular, the Accenture study on the chemicals industry and the circular economy and in particular its methodology to assess the increased looping of chemicals can prove very relevant for use in Flanders on the condition that cross-country cooperation and interactions are included, in particular due to the importance of plastics in the Flemish chemical sector value chain.

The highly technologically focussed DECHEMA, 2017 roadmap gives a comprehensive and detailed overview of future technological options for deep emission reductions in the chemicals industry, including the expected economics (investment needs) of these options.

The similarity between the Dutch and Flemish industrial emission's profile invites a closer look of the recent roadmaps developed there (e.g. McKinsey & Co, 2017; Wuppertal/Port of Rotterdam, 2016; and Ecofys/Berenschot, 2018) and an analysis of the different solution pathways and the relevance for Flanders. The McKinsey & Co, 2017, presents two main scenarios with a different strategic vision. One which seeks to meet (short-term) targets at lowest cost and one that seeks more upfront CAPEX in new technologies. While the (short-term) lowest cost scenario might seem attractive it comes with a higher cost on the longer term in the form of higher OPEX beyond 2030 and dependence on foreign developed know-how and technologies.

In particular the Ecofys and Berenschot, 2018 roadmap for the Dutch chemicals association can be used as a template for a Flemish chemicals roadmap, also because it not only looks at the additional CAPEX for low-CO_2 breakthrogh tech in the chemicals industry but also addresses the CAPEX needed outside the industry for infrastructure and production of energy and feedstock for the transition.

The Material Economics report (2019) was the first integrated roadmaps that put a high focus on the circular economy and materials efficiency to achieve climate neutrality. The accompanying policy study Wyns et al., (2019) showed that next to carbon pricing, there will be a need for new instruments such as standards and procurement to advance materials efficiency throughout the economy.

Finally, there is high level of consistency between the policy recommendation across most of the roadmaps and studies considered in this report. They show a clear need for a mission-oriented research, development and, most importantly, demonstration and deployment policy framework. This includes facilitating finance or access to capital. Often the matter of urgency is stressed given the high CAPEX of most low-carbon investments and the fact that investment cycles for energy intensive industries cover a period of 20-30 years, and hence leave limited time towards 2050. Most roadmaps and studies also argue for a coherent and stable regulatory framework for industrial competitiveness and see a strong link with the ongoing energy transition in Europe.

10.5.2 Refining

A list of the roadmaps and studies assessed for the Refining sector is provided below.

Table 12: List of refining sector roadmaps and studies assessed.

REFINING SECTOR					
	Published:	Name	Author:	Scope:	Decarbonsation Scenarios
Roadmaps	2018	The EU Petroleum Refining Fitness Check: Impact of EU Legislation on Sectoral Economic Performance	Concawe	EU refining sector	20-30% (2030), 70% (2050 with CCS, 50% w/o CCS)
Studies	2015	The EU Petroleum Refining Fitness Check: Impact of EU Legislation on Sectoral Economic Performance	JRC IPTS	EU Refining Sector	
	2020	Role of e-fuels in the European transport system - Literature review	Concawe	EU E-fuels	

Table 13: Overview of refining sector roadmaps

Name: Published:	**The EU Petroleum Refining Fitness Check: Impact of EU Legislation on Sectoral Economic Performance** 2018
Author: Scope:	Concawe EU 2050
Scenario 1	**2030 Scenario** **Mitigation**: -20-30% (by 2030)
Scenario 2	**2050 Scenario** **Mitigation**: -70% (by 2050 with CCS, -50% w/o CCS) **CAPEX**: €40+ Bn
Technology Portfolio (included in roadmap and irrespective of scenarios)	Energy Efficiency, Low Carbon Energy Sources, CO2 Capture (combination of CCS and steam reforming plants).
Assumptions	Constant refining capacity (EU 2030 level), all options are exercised, different rates of deployment of technology, energy prices & degree of electricity grid decarbonization.

Key Takeaways for Flanders

The challenges in the EU-focused roadmaps and studies mirror challenges of the sector in Flanders given the intrinsic set up of the sector. Mitigating GHG emissions in the existing refining sector will be challenging and likely costly. There is scope for emissions reductions via electrification and low-CO_2 H_2 production. However, the bulk of the emissions reductions in refining will have to be realised via CCS. The latter will be technically challenging and relatively expensive for refining because of the complexity of refining installations and the diverse sources of GHG emissions inside the plants. This will make carbon capture and storage more expensive in refining and might not lead to achieving net-zero emissions. However, the refining sector will be faced with a bigger transition towards electrification in transport and the buildings sector which will require reassessing the exisiting business models in the refining and fuels industry. Hence, investing in synthetic fuels and advanced biofuels for shipping, aviation and industrial applications which will still play an important role in a climate neutral economy might be the way forward.

10.5.3 Steel

A list of the roadmaps and studies assessed for the Steel sector is provided below.

Table 14: List of steel sector roadmaps and studies assessed.

STEEL SECTOR					
	Published:	Name:	Author:	Scope:	Decarbonsation Scenarios
Roadmaps	2012	Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron & Steel Industry	JRC	EU 2010-2030	14%, 16-21%, 15-19%
	2013	A Steel Roadmap for a Low Carbon Europe 2050	EUROFER	EU - 2050	13%, 38%, 57%, 80%
	2014	Energy transition - mission (im)possible for industry	McKinsey & Company	Dutch industrial sector 1990-2050	40% by 2030, 60% by 2040, 95% by 2050
	2018	Steel Roadmap	Sweden	Sweden - 2050	Net-0
	2019	ARCELORMITTAL CLIMATE ACTION REPORT 1	Arcelor Mittal	EU - 2050	Net-0
	2019	"LOW CARBON ROADMAP: PATHWAYS TO A CO2-NEUTRAL EUROPEAN STEEL INDUSTRY"	Eurofer	EU - 2050	10%, 15%, 74%, 80%, 86%, 95%, 79%
	2019	"Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry"	Material Economics	EU - 2050	100%

Studies	2015	Industry windfall profits from Europe's carbon market 2008-2015 How Energy-Intensive Companies Cash In On Their Pollution At Taxpayers' Expense	Carbon Market Watch	EU Energy Intensive Industries	
	2017	Strategic Research Agenda	ESTEP	EU 2018-2030	
	2017	The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research	Wesseling et al.,	EU energy intensive industries	
	2018	Filling gaps in the policy package to decarbonise production and use of materials	Climate Strategies and DIW Berlin	EU Basic Materials (here: Checicals)	
	2018	Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe	Wyns et al.,	EU Energy Intensive Industries	
	2018	Climate Innovations in the Steel Industry	Lechtenböhmer et al.,	EU Steel Sector	
	2019	CRACKING EUROPE'S HARDEST CLIMATE NUT How to kick-start the zero-carbon transition of energy-intensive industries?	Carbon Market Watch	EU Energy Intensive Industries	
	2019	Building blocks for a climateneutral European industrial sectors	Climate Strategies	EU Energy Intensive Industries	
	2019	Industrial Transformation 2050 – Towards an Industrial Strategy for a Climate Neutral	Wyns et al.,	EU Energy Intensive Industries	

Below - Table 15: Overview of steel sector roadmaps

Name:	Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron & Steel Industry	A Steel Roadmap for a Low Carbon Europe 2050	Energy transition - mission (im)possible for industry	Steel Roadmap	ARCELORMITTAL CLIMATE ACTION REPORT 1	"LOW CARBON ROADMAP PATHWAYS TO A CO2-NEUTRAL EUROPEAN STEEL INDUSTRY"	"Industrial Transformation 2050 Pathways to Net-Zero Emissions from EU Heavy Industry
Published:	2012	2014	2014	2018	2019	2019	2019
Author:	JRC	EUROFER	McKinsey & Company	Sweden	Arcelor Mittal	Eurofer	Material Economics
Scope:	EU 2010-2030	EU 2050	Dutch industrial sector 1990-2050	Sweden - 2050	EU - 2050	EU - 2050	EU - 2050
Scenario 1	**Baseline scenario (BS)** **Mitigation**: -14%	**Economic** **Mitigation**: -13%	**Reference** **Mitigation**: -40% by 2030	**Decarbonisation** **Mitigation**: Net-0	**Clean Power** **Mitigation**: Net 0	**Business as usual** **Mitigation**: -10%	**New Process Pathways** **Mitigation**: -100% **Costs:** Electricity Input ↑ +113% or 335TWh/Yr **Investments**: In Crude Steel Production Capacity ↑ 60%
Scenario 2	**Alternative scenario 1(AS1).** Two cases: 2x-Fuel price and 5x-Fuel price (of BS scenario) **Mitigation**: -16% (for 2x-Fuel), -21% (for 5x-Fuel)	**Maximum theoretical Abatement w/o CCS** **Mitigation**: -38%	**Cheaper route** **Mitigation**: -60% or 20 Mt CO2 by 2040 **Costs**: Electricity demand ↑ 215 PJ (renewable ↑ 64 GW), cost @ EUR 21-23 Bn; **Investments**: 20%; 80% negative payback, energy demand (including feedstock) -12%		**Circular Carbon** **Mitigation**: Net 0 **Costs** : CAPEX + OPEX. Smart Carbon (BFBOF+CCS) (+20-35%)	**Ongoing retrofit' pathway** **Mitigation**: -15% **Costs:** Electricity 55Twh/y **Investments**: Overnight Investment: €34 Bn, CAPEX+OPEX - €74-91/yr.	**Circular Economy Pathway** Mitigation: -100% Costs: Electricity Input ↑ 72% or 200TWh/yr Investments: In Crude Steel Production Capacity ↑ 25%
Scenario 3	**Alternative Scenario (AS2).** Two cases for CO2 price:100€-CO2 and 200€-CO2 **Mitigation**: -15% (100€-CO2) -19% (200€-CO2)	**Maximum theoretical Abatement with CCS** **Mitigation**: -57%	**Steeper route** **Mitigation**: -95% or 46 Mt CO2 by 2050 **Costs**: EUR 71 Bn until 2050		**Fossil Fuels with CCS** **Mitigation**: Net 0 **Costs**: CAPEX + OPEX. Blue H2 DRI (+30-55%), DRI-EAF+CCS (+35-55%), BFBOF + CCS (+30-50%)	**Current projects' pathway with low-CO2 energy** **Mitigation**: -74% (or 221 Mt CO2) (67% without CCS) **Costs**: Electricity: 162Twh/yr for steel production, 234 TwH/yr for H2 production; 5.5Mt/yr H2 use;21MtCO2/yr CO2 stored **Investments**: Overnight Investment: € 52 Bn. CAPEX+OPEX - €81-112/yr	**Carbon Capture Pathway** **Mitigation**: -100% **Costs**: Electricity Input ↑ +72% or 200TWh/yr **Investments**: In Crude Steel Production Capacity ↑ 65%
Scenario 4		**Emissions Reductions with BTT** **Mitigation**: -80%				**Alternative pathway with low-CO2 energy** **Mitigation**: -80% **Costs**: Electricity: 132-165Twh/yr for steel production, 119-275 TwH/yr for H2 production; 2.8-6.4Mt/yr Hydrogen use; 63MtCO2/yr CO2 stored **Investments**: Overnight Investment: € 58 Bn. CAPEX+OPEX - €86-117/yr	
Scenario 5						**Current projects' pathway with CO2-free energy** **Mitigation**: -86% **Costs**: Electricity: 162Twh/yr for steel production, 234 TwH/yr for H2 production; 5.5Mt/yr Hydrogen use; 21MtCO2/yr CO2 stored **Investments**: Overnight Investment: € 52 Bn. CAPEX+OPEX - €81-112/yr	
Scenario 6						**Alternative pathway with CO2-free energy** **Mitigation**: -95% **Costs**: Electricity: 132-165Twh/yr for steel production, 119-275 TwH/yr for H2 production; 2.8-6.4Mt/yr Hydrogen use; 63MtCO2/yr CO2 stored **Investments**: Overnight Investment: € 58 Bn. CAPEX+OPEX - €86-117/yr	
Scenario 7						**Stagnation Scenario - Current Projects Pathway** **Mitigation**: -79%	

Technology Portfolio (included in roadmap and irrespective of scenarios)	Corex/Finex ironmaking MIDREX EnergIron/HYL Direct Sheet Plant (DSP) CCS Top Gas Recycling Blast Furnance (Under ULCOS programme) HIsarna (Under ULCOS programme) ULCORED (Under ULCOS programme) ULCOWIN (Under ULCOS programme)	BF-TGR, ULCORED/HIsarna CCS Electrification of heating Hydrogen-based reduction Electrolysis	Energy efficiency, Electrification of heat demand, Change of feedstock, Develop routes to reuse and recycle materials, Decide on steel production route(s), Develop CCS/U	Develop technologies: H2 to reduce iron ore to iron (which at the current level of production means an increased need of about 15 TWh electricity) Bio coke for reduction of iron ore for powder production and for scrap melting processes (requires a suitable source of carbon, processes for coke production and access to biomass for bio coke at a cost equal to that of fossil coke which at the current level of production requires at least 1-1.5 TWh) Bio-based gas as a substitute for the fossil fuels used in heating and heat-treatment processes where electrification is not an alternative (the estimated need is at least 2-3 TWh at the current level of production).	Torero: reducing iron ore with waste carbon IGAR: reforming carbon to reduce iron ore Carbalyst®: capturing carbon gas and recycling into chemical Carbon2Value: capturing fossil fuel carbon for storage or reuse H2 Hamburg: reducing iron ore with hydrogen Siderwin: reducing iron ore via electrolysis	H2-DRI-EAF, IBRSR – CCS, ETGR – CCU, BFBOF – CCU, BFTGR/BOF - CCS	CCU SR+CCS H-DRI Low-CO2 EAF
Assumptions	EU steel demand will still be 8% lower in 2030 compared to 2007, EU steel exports will decline in future, from traditionally being a net exporter to becoming self-sufficient in steel by 2030, Scrap requirements will increase. Availability of home and prompt scrap is expected to decrease. The recovery of obsolete scrap is expected to fall and remain relatively low. Scrap recovery rates are also expected to rise from their current 50% to 58%, **BS scenario**: demand for steel and, prices of fuels and resources evolve according to the projection of the European Commission. **AS1 scenario**: increase of fuel and resource price **AS2 scenario**: variations in CO2 emission price There will be no more than six retrofits for the integrated and secondary steel route per year.	Increased scrap availability, Greater share of EAF steelmaking, Continuous decarbonisation of power sector, Continuous market growth.	The roadmap scenarios clearly distinguish between efficiency improvements, system developments and technological innovations. Demand side measures focus strongly on circular economy (reuse, remanufacturing and recycling) influenced by the 'Nederland circulair in 2050'.	Ensure a solid base for global competitiveness., Ensure financing for long-term research and knowledge development, also ensuring that the government campaign Industriklivet (Industrial stride) is maintained over parliamentary terms., Provide secured access to electricity and bio-based energy at internationally competitive costs., Facilitate increased collection of steel scrap and support the development of refined sorting of scrap., Invest more and faster in climate-smart means of transport., Assure efficient and predictable permit processes, including required time plans and adaption of legal frameworks to European legislation., Contribute to a larger visibility by supporting further development of qualified life cycle-based models for declaration of climate impact.	**Commercial Horizon**: Iron Electrolysis (20-30yrs), Green Hydrogen DRI (10-20 yrs), Smart Carbon (5-10 yrs), Blue H2 DRI (10-20 yrs), DRI-EAF+CCS (5-10 yrs), BFBOF+CCS (5-10 yrs) Policy Needs: green border adjustment, energy infrastructure and allocation by sector, Update the benchmark methodology for free allocation in Phase 4 of the EU ETS to make it technically feasible, private and public investment support. **Policy Scenarios**: Stagnate, Wait, Accelerate Regionally, Accelerate Globally. **3 key underlying principles**: Supporting the advancement of renewable energy, Accelerating the circular economy, Creating industrial symbiosis.	**BAU Scenario**: assumes that no technological development takes places; no new processes come on stream; the production mix remains the same and projected demand is met using existing installed capacity. **Ongoing Refrofit Scenario:** assumes an 'ongoing retrofit' of existing facilities pathway, which keeps the current share of production technologies, namely Blast Furnaces/Basic Oxygen Furnaces and Scrap-Electric Arc Furnaces, constant until 2050. **Alternative pathways Scenario**: assume a combination of Scrap-EAF and the lowest emission technology from CDA and SCU respectively and are used with green electricity and green gases. **The roadmap assumes** - marginal production growth up to an annual production of 200 million tonnes of crude steel in 2050, which represents a growth rate of about 0.5% growth per year compared to 2010 production levels overlaid on a supposed technology mix for the 'current project' pathway. - Were EU steel production to continues to stagnate, remaining at the 2015 level (166 million tonnes of crude steel), the emissions reduction level could in fact be higher than if production growth were to continue to rise until 2050, as estimated in this study. - The initial setup of the 'current projects' pathway assumes a power grid mix of 80g CO2/kwh in 2050, focuses on the core stream emissions, and hinges on the assumption of a 'closed loop' in 2050 for all CCU products. - A transformed, future EU steel sector will have substantial demand for energy estimated to be around 400 TWh/year, consisting both of low-carbon electricity purchased from the grid for steel production processes (about 162 TWh/year) and the production of about 5.5 million tonnes of green hydrogen (about 234 TWh/year). - Scrap availability increases at 0.5% per year upto 2050. - In the stagnation scenario the 'current projects' pathway could result in emissions of 64 million tonnes of CO2 in 2050. This represents a reduction of up to 79% versus 1990 levels. This scenario could occur if EU imports of semi-finished and finished steel products were to further increase, displacing production of crude steel in the EU.	Steel production stabilises at around 190 Mt from the 2040s as the steel stock saturates at 13.7 tonne steel per capita., In a high recycling scenario, the scrap share of steel production would reach 70%. In a low-scrap scenario, scrap-based inputs would stay between 50% (today's level) and 60%., Depending on how demand develops, the EU would then export as much as 38-63 Mt of scrap per year by 2050.

Key Takeaways for Flanders

The different and evolving roadmaps and studies for the steel industry are moving in the direction of two main routes for climate neutral steel production. The first one being H2-based steelmaking via Dri-EAF. The second one, a combination of technologies that reduce emissions in BF-BOF steelmaking and capture utilise and/or store the remaining emissions. Given that Flanders has a large incumbent BF-BOF route, it seems likely that over the next years, the latter option will be most relevant for Flanders. However, recent studies but also investments in H2-based steelmaking and necessary H2 infrastucture might accelerate the learning curve for H2-based steelmaking and hence could, depending on the cost of H2, make it a very competitive business model for steelmaking as from 2040. On the other hand, the mitigation pathway for BF-BOF offers important options for industrial symbiosis between steel, chemicals and even the food industry. Hence, for Flanders, successful application of low-CO_2 technologies for BF-BOF will heavily depend on the materialisation of this industrial symbiosis in Flanders and neighbouring countries. Important technologies in the BF-BOF route are already being implemented in Flanders. Regardless of the options chosen for low-CO_2 steelmaking, international competitiveness will remain a critical issue over the next decade. Hence, a large majority of these roadmaps and studies stress the need for a policy framework that addresses the loss of international cpmpetitiveness through policy intervention.

10.5.4 Paper

A list of the roadmaps and studies assessed for the Paper sector is provided below.

Table 16: List of paper sector roadmaps and studies assessed.

PAPER SECTOR					
	Published:	Name:	Author:	Scope:	Mitigation
ROADMAPS	2011	Unfold the Future - 2050 Roadmap to a low-carbon bio-economy	CEPI	EU 1990-2050	25% (from 2010, 50-60%, 80%
	2017	Investing in Europe for Industry Transformation: 2050 Roadmap to a low-carbon bio-economy	CEPI	EU 1990-2050	80%
STUDIES	2013	The Two Team Project Report	CEPI	EU Pulp and Paper Sector	

Table 17: Overview of paper sector roadmaps

Name:	Unfold the Future - 2050 Roadmap to a low-carbon bio-economy	Investing in Europe for Industry Transformation: 2050 Roadmap to a low-carbon bio-economy
Published: Author: Scope:	2011 CEPI EU 1990-2050	2017 CEPI EU 1990-2050
Scenario 1	**All equipment replaced with BAT** **Mitigation**: -25% (from 2010) **Investments**: €6 Bn / yr compared to recent investment levels of €5.5 Bn/yr	**Scenario** **Mitigation**: -80% **Investments**: 40% ↑ than current levels. Extra €24 Bn by 2050 for decarb measures and €20 Bn for production of new bio-based products.
Scenario 2	**Implementation of BAT, emerging technology (ET) and current investment patterns** **Mitigation**: -50 to 60% **Investments**: Investments in emerging technologies ↑ 10% extra (global pulp and paper sector"	
Scenario 3	**Breakthough technology developed and available by 2030** **Mitigation**: -80% **Investments**: Assumption that BTT enter the market at no more than 10% greater cost than existing or ET	
Technology Portfolio (included in roadmap and irrespective of scenarios)	**In paper production**: machine's drying section, layered sheet-forming, advanced fibrous fillers and selective fractionation processes to reduce heat demand in paper production. **In pulp production:** the focus is on improving efficiency of existing processes (notably in refining and grinding for mechanical pulp production and the use of wood chops to reduce electricity consumption) **For wood**: laser cutting technologies, material savings, wood drying concepts and development of glues, paints, coatings and further treatment for increasing durability of wood (p.22). Other ET in energy conversion, biomass and waste/residue gasification, black liquor gasification, torrefaction, carbonisation and pyrolysis are also considered., Increased recycling and better sorting., CCS., Industrial symbiosis- integrated biorefinery complexes., CHP.,	Energy efficiency improvements., Demand-side flexibility., Fuel switch., Emerging and breakthrough technologies., Carbon reduction from purchased electricity., Transport improvements.
Assumptions	The expected decarbonisation of electricity, carbon neutrality of biomass, availability of CCS and the realisation of energy efficiency targets, -Accepts Commission's assumption that a projected rise in CO2 price from 17 euro/t in 2010 to 190 euro/t in 2050 will have consequences that drive coal replacement, boosting demand for wood for energy by 35% from 2010-2050., Expected rise in imports of biomass or wood, rejecting that Commission's prediction that imports will not increase to meet demand for large-scale electricity production., Growth of industry to be in line with EU GDP of 1.5% a year for 40 years, with 50% more added value by 2050.	Value added compared to 2010 to increase by 50%, Shift to the circular bioeconomy

Key Takeaways for Flanders

The Flemish paper industry is not a large sector in Flanders. Significant amount of paper and cardboard in produced via recycling. Paper routes that do not depend on recycled materials do only a limited amount of pulping or even import all pulp from outside Flanders. Chemical pulping is not present in Flanders. This implies that the relevance of the paper sector roadmaps and studies is limited to the parts of the paper making process that do not consider pulping (chemical pulping), and in particular, improving the efficiency of the paper making process itself. With regard to efficiency, energy reduction in the process of removing water from the pulp or recycled paper fibres is important. As is heat recovery and the use of alternative fuels. Thus, the paper sector roadmaps and studies, which tend to focus on the use of chemical pulping, including the use of by products of the pulping process, remain of little or no relevance to Flanders. The CEPI (EU paper industry) 2017 roadmap's approach however, which links the ambition level to double the value added of the industry to generate the capital to invest in low-carbon technologies offers an extremely strong (but also realistic) logic. It is therefore recommended to evaluate such dual track (value added and investments for mitigation) in Flanders.

10.5.5 Food

A list of the roadmaps and studies assessed for the Food sector is provided below.

FOOD SECTOR					
Roadmaps	Published:	Name:	Author:	Scope:	Mitigation
Roadmaps	2013	'Een CO2-, water- en afvalneutrale Vlaamse voedingsnijverheid tegen 2030: onderzoek naar haalbaarheid en uitwerking mogelijke aanpak'	NE, VITO, IDEA, KU Leuven	Flemish Food Sector	

Table 18: List of food sector roadmaps and studies assessed.

Key Takeaways for Flanders

This study and its approach form a highly interesting template for a broader industrial low-carbon roadmap for Flanders. This comes from the fact that the food-sector roadmap not only tackles GHG emissions but also addresses waste and water resources in an integrated manner (including an assessment across food-sector related value chains). The food roadmap furthermore sets very specific ambition levels (e.g. KPI's) in each of these areas and has developed a toolbox of possible actions. While the roadmap shows a theoretical high potential for achieving 'neutrality' targets, it also highlights major barriers for practical implementation. The report further highlights possible conflicts between energy and raw materials demand (for instance, the energetic use of organic waste vis a vis their use as a circular resource in other sectors). Both, the highly interesting scientific approach and the integrated assessment across GHG emissions, waste (circular economy) and the energy system, make this roadmap's approach a good example for replication in a broader industrial low-carbon framework for Flanders. Importantly, the know-how for the implementation of such an approach resides within Flemish research institutes and should hence be easily accessible.

10.6 Conclusions

Flanders finds itself in the midst of a vibrant industrial region moving steadily towards climate neutrality. Looking at the four key countries surrounding Flanders, namely, France, The UK, The Netherlands and Germany, it is notable that the policy instruments such as a climate law, an industrial policy or a hydrogen strategy which all neighbouring countries have in place now (with the exception of France which currently does not have an industrial strategy) are absent in Flanders. In particular, it would be essential for Flanders to also develop an Industrial Strategy which could provide direction and a reliable framework for industry to transition to climate neutrality. A hydrogen strategy would be extremely beneficial too not only to ascertain the amount of hydrogen that could be produced in Flanders for 2050 and the related infrastructure needed, but to guide an external hydrogen energy/trade policy given a large proportion of Flanders' hydrogen needs are expected to be met through imports, similar to Germany. Moreover, a legal framework would provide guidance and long-term legal certainty to the economy at large. It also allows the possibility to embed legally strategic instruments like an industrial strategy or a hydrogen strategy, in addition to important funding mechanisms which tackle the grand challenges. Finally, the various roadmaps and studies show that across a range of industries (steel, chemicals, refining and paper) in theory emission reductions mitigation of up to 100% compared to different historical baselines are possible but challenging. Evidently, the technological options and scenarios presented in the roadmaps and studies will have to be applied and calibrated to the specific Flemish context.

11. Flemish Policy framework

11.1 Current policy framework in Flanders

11.1.1 Policies and strategies

In Flanders, strategies, policies and instruments which guide the industry climate transition are well in place. The most prominent of these are:

- The Flemish energy vision (Vlaamse energievisie)
- The Flemish long-term vision (Vlaamse langetermijnvisie)
- The Flemish Climate Policy Plan 2021-2030
- The Flemish action plan on the circular economy (Vlaanderen circulair)
- Voluntary agreements on industrial energy efficiency (Energiebeleidsovereenkomsten)
- Flemish innovation and investment support
- Financing vehicles (PMV)

In March 2018, the Flemish Government approved the updated **long-term vision for Flanders entitled 'Visie 2050'** which endorsed the United Nations Sustainable Development Goals (SDGs).[309] Visie 2050 identifies seven transitions: energy transition, future climate change policy, smart living, mobility, the circular economy and Industry 4.0. R&I is seen as a cornerstone of these seven transitions. Both Visie 2050 and the United Nations 2030 Agenda for Sustainable Development are strategic documents served as the basis for **Visie 2030**, a framework of 48 objectives the Flemish region seeks to achieve by 2030. Many objectives from the Visie 2030 are contained in sectoral long-term policy plans in preparation, for example the Flanders Policy Plan for Space, the Energy and Climate Plan 2021-2030, the Mobility Plan, the Air Plan and the Housing Policy Plan. These plans also follow their own development trajectory and after approval, the 2030 objectives will form an integral part of the 2030 framework. Specific indicators have been developed to make the realization of the 2030 targets concrete and measurable. Additionally, in the short term, one of the objectives is to reach the target of 3% R&D spending in Flanders.

In December 2019, the Flemish Government approved two coordinated plans: the draft Flemish Energy Plan 2021-2030 and the draft Flemish Climate Policy Plan 2021-2030. The **Flemish energy plan 2021-2030** defines the Flemish government's contribution to the EU's energy efficiency and renewable energy targets by 2030. It essentially relies on a fast-track approach, supported by five pillars (energy efficiency, renewable energy, flexibility, funding and governance) which underpin the vision. It also makes proposals to make energy infrastructure smarter and more flexible. With regard to energy intensive industries, the strategy recommends continuing the voluntary agreements on energy efficiency (energiebeleidsovereenkomsten - discussed below). It further recommends stimulating innovation and the transition to a circular economy and calls for the support of private sector driven demonstration projects. These

[309] The United Nations Sustainable Development Goals (SDGs) set out in the United Nations resolution entitled 'Transforming our World: the 2030 Agenda for Sustainable Development', ratified by the General Assembly on 25 September 2015

innovative activities of the public, research and private sectors can be concentrated in well outlined clusters. Finally, the strategic document mentions industry achievable commitments with quantifiable results (e.g. on energy-efficiency) while maintaining competitiveness. Additionally, according to the vision, it can be investigated if roadmaps could be developed or published. The **Climate Policy Plan** on the other hand, outlines Flemish climate policy for the period 2021-2030 to achieve final energy consumption of 21.6 Mtoe in 2030 or final energy saving of 4.5 Mtoe in 2030 compared with PRIMES 2007.

'Vlaanderen circulair'[310], established in January 2017, is the masterplan to successfully achieve Flanders' transition to a circular economy. The plan consists of six core activities:

- The creation of partnerships, co-creation and shared ownership
- Financial support for pioneering innovators
- Sharing of knowledge and policy relevant research support
- Supporting policies and coordination between different branches of government
- Support and accelerate innovation and entrepreneurship towards a circular economy
- Anchoring and scale up of best practices on circular economy.

Government support is driven by the needs of stakeholders who will take the initiative in this area. Main work programmes are the Green Deal on circular public and private procurement, the circular city and circular entrepreneurship.

Voluntary agreements on energy efficiency in industry (Energiebeleidsovereenkomsten)

On 4 April 2014, the Flemish Government approved energy policy agreements for anchoring and sustaining energy efficiency in the Flemish energy-intensive industry (non-VER companies & VER companies, VER companies being EUETS installations) for the period 2015-2022. The voluntary agreements on energy efficiency for EU ETS companies started in 2015 (and were a continuation of previous programmes on energy-efficiency benchmarking covenant and auditing covenant). The main goal of these voluntary agreements is to have energy intensive companies strive towards or maintain excellence in the area of energy efficiency. VER and non-VER companies that accede to an energy policy agreement are committed, among other things, to have an energy audit carried out every four years and to draw up an energy plan based on the results of that audit. The latest results from the implementation of the voluntary agreements show an aggregated list of efficiency measures by these companies leading to a reduction of energy use of 17.4PJ in 2018 compared to the year 2014.

Flemish innovation and investment support

For Flanders, there is strong conviction that the solution to the climate crisis can also be found in R&I that accelerates innovation needed to achieve the energy transition and create a climate-friendly society. Flanders has two chief funding agencies that are responsible for implementing R&I policy, including in support of Energy Union priorities: The **Scientific Research**

[310] Vlaame Overheid, n.d.,; Vlaame Overheid, 2017

Fund (FWO) and The Flemish Agency for Innovation and Entrepreneurship (VLAIO). Both agencies have a bottom-up approach and finance projects across all scientific fields. The FWO finances basic and strategic scientific research in all scientific fields at universities and research facilities in the Flemish Community.

In support of innovation and investments in large industrial companies, the Flemish government has a range of instruments. The maintenance and coordination of these initiatives is done by The **Flemish Agency for Innovation and Entrepreneurship (VLAIO)**. VLAIO's own arsenal includes both instruments for providing economic support to companies and mechanisms for financing innovation within the business community. In the area of R&I, VLAIO also offers support for innovations at the pilot phase. VLAIO's grants cover the entire spectrum of R&I projects, including energy and climate (energy efficiency, renewable energy technologies, energy systems, energy storage, carbon capture, use and storage (CCUS). VLAIO also supports Flemish clusters (both innovative business networks and high-tech clusters – see below).

The two funding agencies FWO and VLAIO encourage European R&I cooperation under the Horizon 2020 programme, notably through participation in ERA-NET Cofund instruments, Joint Programming Initiatives (JPIs) and EUREKA. With regard to Energy Union initiatives and, in particular, initiatives aimed at achieving the strategic objectives of the SET-Plan, Flanders is involved in the Cofunds for SOLAR-ERA.NET and the ERA-NET SES RegSys (Smart Energy Systems Focus Initiative on Integrated Regional Energy Systems). Flanders also participates in the JPI Urban Europe through the ERA-NET 'Sustainable Urbanisation Global Initiative' Cofund.

The Flemish Government also funds R&I through an annual grant to the four **Strategic Research Centres (SOCs)**. The SOCs involved in R&I within the Energy Union are VITO (Flemish technological research institute), IMEC (research institute for microelectronics and nanoelectronics, including research in digital technologies for healthcare, smart electronics, sustainable energy and transport) and Flanders Make (smart manufacturing with a focus on product and production technology in the automotive, smart machine and manufacturing sectors).

In 2015, the Flemish Government approved the introduction of a cluster policy in Flanders through a **Cluster Policy Concept note**. The aim was to tap into latent economic potential and boost the competitiveness of Flemish companies through active and sustainable cooperation between all actors with direct economic value added for the Flemish business community. Two types of clusters have been established and have benefited from organisational support, namely spearhead clusters and innovative business networks (IBN). High-tech clusters also receive a dedicated project budget. International cooperation is essential for these clusters to function. The spearheid clusters connect to important strategical domains in Flanders and are large-scale triple helix initiatives that receive financing for up to ten years to develop and implement their competitiveness programme. The Innovative Business Networks are usually smaller, bottom-up initiatives, receiving support for a period of three years to organise a collaboration dynamic in a specific domain that could lead to the increased competitiveness of companies.

The six spearhead clusters are:

- SIM: Spearhead cluster for materials
- Flanders Food: Spearhead cluster for agrofood
- The Blue Cluster: Spearhead cluster for blue growth (maritime related sectors)
- VIL: Spearhead cluster for logistics and transport
- FLUX50: Spearhead cluster for energy
- Catalisti: Spearhead cluster for sustainable chemistry and synthetics

Catalisti is also responsible for the **Flanders industry innovation moonshot**. From 2020 to 2040, the Flemish Government will invest 20 million euros in Flanders Industry Innovation Moonshot every year, totalling 400 million euro. These funds will, through innovative research, enable the development of breakthrough technologies by 2040. Thanks to these technologies, the Flemish industry will be able to implement new climate-friendly processes and produce new climate-friendly products. These innovative products and processes will help Flanders to make the big leap: making its industry carbon circular and low in CO_2 by 2050, reducing its CO_2 emissions, and meeting its climate commitments. Moonshot defines 4 global themes: 'Bio-based chemistry', 'Circularity of carbon in materials',' Electrification and process transformation ',' Energy innovation ':

1. **Bio-based chemistry** is investigating how renewable and climate-friendly raw materials such as biomass can replace polluting fossil raw materials. Projects involving lignin (a type of natural waste), sugar as a raw material and biorefineries are supported in this project.
2. **Circularity from carbon in materials** the emphasis is on research into the recycling and reuse of plastics. Specifically for this year, this concerns projects concerning the recycling of polyolefins, the recycling of polycondensation polymers such as polyesters and polyamides and Design for recycling for thermosetting materials such as epoxies and resins.
3. **Electrification and process transformation** aims to electrify industrial processes and make them CO_2-smart. In 2019, the Flemish Government will support projects related to electrification of polyolefin and ammonia production, conversion from CO_2 to CO, CO_2 capture in this process.
4. Since the Flemish industry is extremely energy-intensive, renewable energy is central to the fourth research project **Energy innovation**. For 2019, this concerns research on the themes of hydrogen transport and storage, hydrogen production, advanced heating systems, energy flexibility and a cross-sectoral framework for energy-intensive industry. This is done in close collaboration with flux50, the spearhead cluster for energy.

Within Flanders Industry Innovation Moonshot, 9 new research projects are starting, which account for EUR 12,364,705 of the 20 million euros in subsidies that the Flemish Government made available for this innovation program in 2019.

Finally, a catalyst for innovative investments in Flanders is **Participatiemaatschappij Vlaanderen (PMV)**. PMV[311] provides finance for promising businesses from the very start through their various growth stages and even on to operating internationally. Working with and for the government and other partners, PMV implements projects that are important for prosperity and wellbeing in Flanders. PMV is co-financing the Bluechem sustainable chemistry incubator. It is almost certain that an industrial low-carbon transition in Flanders will require access to risk mitigating capital. Organisations such as PMV will have to play an important role here also because of their ability to leverage other EU de-risking instruments (e.g. via the European Investment Bank (EIB)).

11.1.2 Below - Overview of Flemish and EU incentives for CO_2 reductions

[311] PMV, 2018

Table 19: Incentives for CO_2 emission reduction activities in Flanders Overview (1/2)

Name of the incentive	Provider	Form	Intensity	Short description
Increased investment for energy-saving investments	Federal government via Flemish Energy Agency ('VEA')	deductionTax deduction	• 13.5% of the purchase or investment value of the investments made during the taxable period	The investments that qualify should aim at a more rational use of energy in industry, in particular at improving industrial processes purely for energy reasons.
Ecology+ (EP-PLUS)	premiumFlemish Agency for Innovation & Entrepreneurship ('VLAIO')	Subsidy (non-fiscal)	• Up to 45% subsidy percentage (go) • Up to 55% subsidy percentage (SME) • Maximum total amount: 1,000,000 EUR over a three-year period (possible deviation depending on the impact of the subsidy on Flanders).	Awarded only to technologies that are on an exhaustive technology list (LTL): • Environmental Technologies • Energy Technologies • Renewable Energy.
Strategic ecology support (STRES)	VLAIO	Subsidy (non-fiscal)	• Up to 30% subsidy percentage (go) • Up to 40% subsidy percentage (SME) • Maximum total amount: 1,000,000 EUR over a three-year period (possible deviation depending on the impact of the subsidy on Flanders).	Intended for strategic environmental projects that: • contribute to global solutions (environmental or energy issues) • targeting closed circuits (renewable energy, sustainable use of materials, recovery of materials) that • contain process integrated solutions.
Call green heat, residual heat, heat networks and biomethane	VEA	Subsidy (non-fiscal)	• Up to 65% subsidy percentage for ko • Up to 55% subsidy percentage for mo • Up to 45% for go	Who invests in new projects of: • green heatheat • residualheat • networks • Biomethane production.
Call small and medium-sized wind turbines	VEA	Subsidy (non-fiscal)	• Up to 70% subsidy percentage for ko • Up to 60% subsidy percentage for mo • Up to 50% for go	This support program focuses on the investment in onshore wind turbines with a gross nominal capacity per turbine greater than 10 kWe to 300 kWe.

Table 20: Incentives for CO_2 emission reduction activities in Flanders Overview (2/2)

Name of the incentive	Provider	Form	Intensity	Short description
Reimbursements from your grid operator	Flemish government via the grid operators (Fluvius, Elia)	Subsidy (non-fiscal)	Depending on the nature of the energy-saving investment	The grid operators under the umbrella of Fluvius, just like the operator of local transport network of electricity (Elia) by the Flemish government is obliged to give bonuses if you run into a non-residential building energy-saving investments
Call innovative circular economy projects	Flanders circular and public Waste Agency of Flanders (OVAM)	Grant (non-tax)	• Up 80% subsidy percentage • Maximum amount: EUR 100,000.	Projects that can serve as an experimental, demonstration and dissemination project in the field of circular city or circular entrepreneurship
Subsidies for companies (individual) and for cooperation projects in logistics	Flemish Institute for Logistics ('VIL') and VLAIO	Subsidy (non-fiscal)	• Depending on the nature of the investment. • Up to EUR 3,000,000	This may involve the development of a completely new or significantly innovative (improved) product, process, service or concept, with an important impact on the company. And there are subsidies for setting up pilot projects, developing a business case, developing new knowledge and for research in collaboration with a knowledge institution.
Flanders Industry Innovation Moonshot	Flemish government via Catalisti	Subsidy (non-fiscal)	EUR 20,000,000 every year between 2020 and	2040.The Moonshot is a future-oriented industrial innovation program of the Flemish government. Moonshot defines 4 global themes: 'Bio-based chemistry', 'Circularity of carbon in materials', 'Electrification and process transformation', 'Energy innovation'.
Compensation for CO2 costs related to indirect emissions	Implementation of EU provision in EU ETS	Subsidy (non-fiscal)	Aid intensity of 75% applied in a specific formula	Companies in certain electricity-sectors may have a higher electricity bill as an indirect consequence of the European emissions trading system (EU ETS). The Flemish government wants tothis competitive disadvantage by compensating a limited number of sectors for these CO_2 costs.
Research & Development projects *projects	VLAIO	Subsidy (non-fiscal)	Up to 50% (60%) subsidy percentage for development (research projects)	Financial support for the realization of an innovative innovation or for the expansion or strengthening of their research and development activities.

Table 21: Incentives for CO_2 emission reduction activities in Europe Overview

Name of the incentive	**Provider**	**Form**	**Intensity**	**Short description**
LIFE	European Commission	Subsidy (non-fiscal)	• Subsidy percentage of 55% • Total project budget between 1 and 6 million euros	Subsidies for projects with the objective of demonstrating or piloting products / technologies that are almost ready to be marketed or projects that contribute to mitigation of climate change. The focus of the project must be on sustainable development. The following themes are discussed: water, waste, environmental management, sustainable industrial production, mitigation of climate changes, land use, noise, etc. Each year there is one round in which an application can be submitted.
Connecting Europe Facility ('CEF') Energy	European Commission	Subsidy (non-fiscal)	Subsidy percentage of 55%	Subsidies for projects that focus on the sustainability and modernization of European infrastructure (transport, energy and telecom). Calls are opened every year with specific themes, deadlines and criteria.
Innovation Fund ('IF')	European Commission	Subsidy (non-fiscal)	Subsidy percentage up to 60% of the extra capital and the operational costs related to innovation.	Funding program for the development of sustainable, innovative technologies with a focus on energy-intensive industries, renewable raw materials, energy storage and carbon capture, use and storage.
Horizon 2020 ('H2020')	European Commission	Subsidy (non-fiscal)	• Subsidy percentage of 100% • Projects between 1 and 15 million EUR	Subsidies for research and development projects in various fields: waste, health, raw materials, biotechnology, mobility, factories of the future, sustainable process industry, etc. Calls are opened every year with specific themes, deadlines and criteria.
Public-private Partnerships (BBI, SPIRE, etc.)	Public Partnership between EU and Bio-based industries consortium	Susbidie (non-fiscal) (follows regulation of H2020)	• Depending on project and partnership	Ex. BBI ☐ Subsidy for projects that focus on the development of new biorefining technologies to sustainably convert renewable natural bio-based resources into products, materials and raw materials. Calls are drawn up each year within specific themes: raw materials, biorefining / processes and markets, products and policy. SPIRE ☐ Grants for the development of enabling technologies and *best practices* in various sectors (cement, ceramics, chemistry, engineering, non-ferrous metals, minerals, steel and water) that contribute to improving resource efficiency in the process industry.

12. Annexes

12.1 Annex 1: Roadmaps and Studies

12.1.1 Chemicals Sector

Roadmaps

- Ecofys and Cefic (2013)

This roadmap focuses on the European (EU 27) chemicals industry (scope 1 and scope 2). With 1990 as a baseline, the roadmap develops four different scenarios to 2050 (beginning 2013): 'Continued Fragmentation Scenario', 'Isolated Europe Scenario', 'Differentiated Global Action Scenario', and 'Level Playing Field Scenario' with GHG reduction targets of 40%, 80%, 80% and 50% respectively. The Continued Fragmentation Scenario' assumes the absence of global action against climate change. In the Isolated Europe scenario, the current fragmentation in energy and climate policies with a low global ambition continues, but Europe intensifies its policy ambitions. In the Differentiated Global Action scenario, differentiated global action and limited policy convergence in key economic regions are assumed (global GHG emission reduction of 50%). Finally, in the Level Playing field scenario a global climate change mitigation agreement fosters policies creating a level playing field via a uniform global carbon price signal.

The roadmap makes key competitiveness assumptions. In all the scenarios with the exception of the Level Playing Field scenario, energy price differences between Europe and the rest of the world persist and there is a negative impact on production for basic chemical industries which also affects Specialty Chemicals and Consumer Chemicals. In the Continued Fragmentation and Isolated Europe Scenario, CO2 price signal between Europe and the rest of the world in 2050 increases over time to ± EUR 30 per tonne of CO2 (/t CO2), while that in the Differentiated Global Action Scenario increases to ± EUR 200/t CO2. However, in the Level Playing Field scenario, global energy and feedstock prices as well as industry electricity costs converge over time, there is a similar CO2 price signal worldwide, and value chains are fully integrated in Europe. Under the level playing field scenario, the roadmap sees EU chemicals sales almost double between 2010 and 2050 (from around EUR 500 Bn to around EUR 1000 Bn). In the scenario where the EU undertakes unilateral climate action the figure would barely change in 2050. The net trade ratio (as % of demand) would rise from 10% to almost 15% between 2010 and 2050 in the level playing field scenario, but would drop dramatically to -20% by 2050 in a unilateral action scenario.

The roadmap underscores the following technological options: bio-based feedstock; valorisation of waste and recycling of plastics; CCS; greater process energy efficiency; changes in heat sources, use of renewable energy and CHP; end of pipe emission abatement; reduction of emissions in nitric acid productions; and mitigation options for ammonia, cracker products and chlorine. The roadmap formulates policy recommendations on global climate action and the role of the EU, EU energy policy, the link with GHG mitigation in other sectors and the EU's and national R&D frameworks.

- ECF & McKinsey (2014)

This roadmap focuses on five chemical products in depth throughout their value chains and identifies a 50% to 75% scope 1 and 2 abatement opportunity by 2030 of which 60-70% appears to have a neutral to positive impact on competitiveness. Additional Scope 3 reductions of more than 90 $MtCO_2$ have been identified. While this roadmap has not modeled the total emission reduction opportunity for the industry, the results of the five life cycle assessments are broadly consistent with the CEFIC 2013 roadmap which estimates a 40-50% emission reduction potential by 2030 compared to the frozen technology baseline.

The study emphasizes cross-industry collaboration and details a technology portfolio which includes mature tech implementable in near to medium term (e.g. PVC recyling, retrofit polyurethane insulation in homes and buildings, more efficient chlorine electrolysis technologies, increased re-refinement rate of polyalphaolefins, greener foam blowing agents for polyurethane), products and materials substitution (e.g. replacing polycarbonate with bio-based plastics, switching from polyalphaolefins to bio- based oils, and replacing PAN with lignin or polyethylene in carbon fiber production), renewable feedstock (e.g: renewable carbon in polyol production for polyurethane, using bio-ethylene in PVC production, and replacing phosgene with CO_2 based feedstock in polycarbonate production), shift to renewable energy, CCS and circularity.

Three key assumptions are made: net costs after 2020 depend on further decisions on 2030 EU climate package, the recycling rate increases to 85-95% in production waste and up to 5% in construction waste, and that every lever would be implemented in the near term.

- WI & Port of Antwerp Rotterdam (2016)

The roadmap has a regional scope and focuses on decarbonisation by 2050 of the industrial cluster of the Port of Rotterdam whose annual CO_2 emissions range over 30 Mt. With a baseline of 1990, the roadmap develops four scenarios: 'Business As Usual (BAU)', 'Technological Process', 'Biomass and CCS (BIO)', and 'Closed Carbon Cycle (CYC) scenario and the Closed Carbon Cycle Earlier Closure (CYC-ECE)'.

The BAU scenario targets 30% CO_2 emission reductions: emissions remain stable until 2020, and then gradually decline amidst technical improvements and declining refinery production. The TP scenario targets around 75% CO_2 emission reductions with wide implementation of BAT and tightening of the Emissions Trading System (ETS), expanded renewable electricity for heat generation and H_2 production "at models scale", energy efficiency improvements in all sectors, and CCS at industrial scale. The BIO scenario targets 98% CO_2 emission reductions through major breakthroughs, especially CCS. A key challenge for the scenario is sustainable and affordable sourcing of biomass. The BIO scenario assumes energy-related emissions in the EU to be near-zero by 2050, nearly 100% market share of renewable electricity, that heat and mechanical energy is delivered by electricity, and that remaining thermal power plants connect to a CO2 grid instead of using fossil fuels. Strong policy instruments such as carbon tax, support for implementation of CO2 grids and CO2 storage sites pro, and construction of CO2 pilot grids of 2020 will be needed.

The CYC and CYC-ECE scenarios target around 98% CO2 emission reductions and are identical, with the except that the CYC scenario counts on earlier closure of coal-fired power plants (2019-2025). The CYC and CYC-ECE scenarios are similar to the BIO scenario, but makes different assumptions regarding CCS and biomass: CYC scenario assumes CCS as economically unviable, and sustainable biomass sourcing unnecessary. The CYC scenario is well-suited for Rotterdam harbour given the port's advanced circular and almost carbon-neutral economy status. However, the scenario will require extensive investments to enable technical viability (e.g. methanol-based feedstock, Fischer-Tropsch wax).

The underlying assumptions of the modelling are largely based on EU decarbonisation scenarios and emphasise expected changes in three crucial areas for the port's current industrial cluster: European transport sector fuel demand, final industrial sector energy demand mix and Europe's electricity mix. The roadmap addresses technologies for the energy sector, crude oil refining and transport fuel supply, petrochemical sector, building sector and the transport and logistics sector. It however underscores emission reduction strategies for two vital sectors - petrochemicals (energy efficiency improvements both in processes and in cross sectional strategies; renewable energy as a fuel or heat source; electrification; change in feedstock from mineral oil to natural gas and to carbon feedstock; and CCS/CCU) and buildings (energy efficiency improvements of buildings and technical systems; renewable energy as a fuel, electricity or heat source; and integrated concepts creating synergy effects). Industrial symbiosis implies strong value chain integration and is emphasized in the vertical integration of the petrochemical sector. Demand side reduction measures highlight seven new economic activities and industries: Offshore wind, Bio-based chemistry, Demand-side-management and energy storage, CO2 transport and storage, Synthetic fuels, Carbon-neutral primary steel production and Use of waste.

The roadmap makes the following recommendations to both industry and policy makers: the need for a decarbonisation roadmap, support for the ROAD project, adjustment to the port's business model, emphasizing strategic networking, identifying low-risk and robust investments, providing policy predictability, increase in Carbon Price, schedules for the phase-out of CO2-intensive technologies and subsidised R&D and investments in new low-carbon technologies and infrastructure.

- JRC (2017)

The roadmap conducts a bottom-up assessment of the European chemical and petrochemical industry's potential for energy efficiency and GHG emissions reduction up to 2050 with 2013 as a baseline. In total, 26 basic chemical products were included in the analysis which were found to cover 75 % of the total energy and non-energy use of the industry and the vast majority of the emissions in 2013. Three scenarios were developed: baseline scenario, Fuel price variations (AS1), and CO2 price variations (AS2). For AS1 and AS2, 4 variations are considered: low, medium, high and very high fuel/CO2 prices. In 2050, the low price corresponds to the baseline scenario, the medium is twice the baseline scenario, high prices are five times that of the baseline scenario and very high are ten times higher than baseline scenario. In the baseline scenario, with retrofits, 36% emissions reductions are achieved and small improvement of just only 4% (225 PJ) of total energy consumption by 2050. In AS1, none of the alternative scenarios varying the energy price offers any remarkable difference compared with the baseline scenario as with the industry already incorporates practically all BATs at hand; as well as all potential ITs as soon as they become available which means that energy-efficiency investments of the alternative scenarios are not able to foster additional savings to the already achieved in the baseline scenario. In AS2, the results are quite similar to the baseline scenario; the maximum saving provided by the most favourable scenario delivers 0.8% of additional CO2 to the baseline 36.8 % instead of 36%.

About 50 BATs and ITs considered in this study reduce the electricity, thermal energy or steam consumed in the processes, but not directly the feedstock needed. There are two cross-cutting technologies considered in this study: combined heat and power (CHP) and carbon capture and storage (CCS). Although CHP is already installed to a large extent in the chemical industry, the model foresees the installation of additional 2750 MW of electrical capacity. Mainly in the production of: adipic acid, benzene, ethylbenzene, ethylene dichloride, vinyl chloride monomer, PVC-S and PVC-E. Only 12% of the 9.4 TWh/y electricity produced via CHP is consumed inside the processes, while the excess is sold. On the other hand, the model installs CCS in all three subsectors that are sources of high purity CO2. In the case of ammonia the technology becomes popular only in the part of the industry that is not integrated with urea production, but it is only expected, as CO2 is usually consumed in producing urea. In the hydrogen industry, about 70% of the facilities install CCS, while in the ethylene oxide subsector 80%. The model assumes that some technology innovations will become available at some point in the future. Other basic assumptions include: the plants are operating 24 hours a day during 90 % of the year, the components in the systems behave as ideal gases or ideal solutions, in the environmental analysis, only GHG are considered, unless stated otherwise, natural gas is assumed for the calculation of the emission factors, and if in the information available for the different ITs, there is no clear indication about the year the investment costs refer to, the assumption will depend on the date of the corresponding reference. The report also assumes that European industry remains globally competitive and demand is met with production and an increase by 45.6 % of the demand in the Baseline Scenario.

- Dechema (2017)

This roadmap with a 2050 timeframe focuses on technological enablers for a low-carbon EU chemical sector which, upon implementation, can allow for an estimated 210 Mt CO2/year (max) emissions reduction in 2050. The roadmap develops four scenarios: Business as Usual (BAU), Intermediate, Ambitious, and Maximum. BAU CO2 emissions increase from 85 Mt CO2 to 119 Mt CO2 (or 104,66 MtCO2 with energy efficiency measures), (investments of EUR 2,1 Bn/annum). CO2 emission reductions in the Intermediate scenario are 117 Mt (70 Mt or 59% decrease chemical industry and 47 Mt synthetic fuels – CAPEX EUR 17,0 Bn + EUR 14,1 Bn p.a. for efficiency measures). In the Ambituous scenario, CO2 emission reductions are 80-95% (or 216 Mt of which 101 Mt chemical industry and 115 Mt for fuels) (CAPEX EUR 19,2 Bn + EUR 14,1 Bn p.a. for efficiency measures). In the Maximum scenario, CO2 emission reductions are the highest: 498 Mt in 2050 (chemicals: 210 Mt; synthetic fuels: 288 Mt) (CAPEX EUR 26,7 Bn+ EUR 14,1 Bn p.a. for efficiency measures).

BAU assumes 1% p.a. growth as production volume grows from 100 Mt in 2015 to 140 Mt in 2050. The intermediate scenario assumes continuous process efficiency measures (via retrofits and optimizations), steady deployment of breakthrough technologies, steam generation by electricity and steam re-compression implemented at full scale by 2050, supportive policy measures for 1) an increasing biofuel quota including synthetic fuels from CO2, 2) incentivizing investments in chemical production, and 3) shift from fossil feedstock based processes and 35% new production facilities by 2050. In the ambitious scenario, the share of low-carbon chemical production increases to 50% (via policy support, financial incentives for substitution of fossil feedstock, and economically competitive low-carbon technologies), the share of renewable (including CO2-based) fuels increases to 40%, energy efficiency measures are implemented, electrical steam generation and recuperation is fully deployed, the replacement rate of old plants increases from to 50% BPT level production plants, lighthouse demonstration projects are realized at around 5000 tonnes per annum (t/a) scale and industrial symbiosis potentials are valorised. The maximum scenario assumes 100% deployment of all new technologies (including electric steam generation and steam re-compression) and 100% new production facilities (2.85% p.a. replacement rate). H2 (preferred) and biomass yield 100% of the production in 2050. There is a high amount of low-carbon methanol production for chemicals while the production of synthetic fuels is relatively low and jet-fuel consumption decreases (from 14,000 PJ to 5,300 PJ in 2050).

Technologies at TRL 6 and higher are included. They include: energy efficiency, H2 and CO2 based production routes, biomass and biomass waste streams to chemicals, electricity-based processes, industrial symbiosis and circular economy, CCU, other. In this regard, three aspects are combined: i) improvement of energy efficiency in conventional production plants, ii) transition towards alternative carbon feedstock, and iii) low-carbon electricity (renewable electricity and nuclear power) for energy supply (and electrons as reducing agent) in chemical transformations. Demand-side measures include recycling of polymers and the use of polymer waste as feedstock which could save 57 Mtoe by 2050 energy for feedstock and industrial symbiosis in particular with the steel industry.
Policy recommendations include: the need for a large and ambitious R&I program, PPPs to focus RD&I efforts and enable risk sharing for investments for demonstration of innovative technologies, abundant low-carbon electricity at competitive prices, innovation into new chemical technologies, fiscal structure for greenfield, enhanced cross-sectorial industrial symbiosis opportunities, dialogue with policy makers and the generation of a central European database of CO2 sources and infrastructures, available sustainable biomass and lifecycle data to foster industrial symbiosis.

- IEA, 2017

The roadmap focuses on global energy systems (energy efficiency, decarbonisation, transformation and clean technologies) and with 2014 as a baseline, develops three mitigation scenarios up to 2060: 'Reference Technology Scenario (RTS)', '2DS', and 'B2DS'. In the chemicals and petrochemicals industry, direct CO2 emissions reductions are 975 Mt CO2/year in 2060 in 2DS and 321 Mt CO2/year in 2060 in B2DS (30% of current levels). B2DS reductions are achieved by reducing the SEC/tonne of product to produce ammonia to 10.7 GJ/t 2060 and direct CO2 footprint by 96% to 0.1 t direct CO2/tonne of ammonia production; a 10% decrease in process energy intensity and a 94% decrease in direct CO2 emissions from current levels in Methanol production. In addition, process energy intensity would improve by 21% and direct CO2 intensity more sharply by 89% by 2060 in HVC production. Direct CO2 intensities of primary production are seen reduced 24% - 62% by 2030 in the B2D driven by: energy efficiency improvements, advances towards BAT-level processes, shifts to lower-carbon fuels and feedstocks, and deployment of CCS. Decreased Demand in both 2DS and B2DS is at -4% (17.8 EJ) or 1.3 GtCO2 cumulative savings compared with the RTS achieved through material efficiency, improving collection and processing rates of plastic-based consumer products which means less ammonia (70 Mt), methanol (68 Mt), and HVC (1,292 Mt).

Estimated cumulative investment needs between 2017 and 2060 are USD 6.8-8.0 Tn for RTS, USD 6.3-7.3 Tn for 2DS (30% of which is frchemicals and petrochemicals, 24% iron and steel, 20% pulp and paper, 15% cement and 12% aluminium) and USD 7.0-8.7 Tn for B2DS. The 2DS is the least costly scenario while the B2DS is the costliest (given early replacement of capacity, deployment of more costly carbon abatement options and the rapid deployment of CCS, equipment costs offset these effects). Four main groups of technologies and strategies enable direct CO2 emission reductions in the B2DS: energy efficiency and BAT deployment (42%), innovative processes and CCS (37%), lower carbon fuels and feedstocks (13%) and material efficiency strategies (8%). Low-carbon processes and technologies have been systematically detailed along three groups: 1) Commercial low-carbon process technologies, 2) Innovative low-carbon process technologies at the demonstration phase and 3) Low-carbon innovative process technologies at the R&D phase.

The roadmap makes a list of policy findings: lack of performance standards and fiscal incentives, continuation of fossil fuel subsidies and lack of effective internationally coordinated carbon pricing schemes, poor RD&D, lack of sufficient material efficiency strategies, lack of mapping and integrated assessments, lack of programmes that collect technology-specific energy performance statistics and lack of co-operative frameworks. The roadmap also lists technology, low-carbon innovation and low-carbon energy system-focused short and long term recommendations. Finally, the roadmap makes specific policy implications for the B2DS scenario which includes: more aggressive deployment of policy levers, unprecedented climate policy ambition, higher carbon pricing, stronger incentives, additional support for

RD&D, strengthened cross-sectoral and cross-regional co-ordination on energy technology and carbon mitigation options, long-term stability and visibility of the policy framework for investment decision making and rapid policy actions to support a more rapid scale-up and deployment of innovative low-carbon technologies, de-risking and incentive mechanisms

- Accenture (2017)

The roadmap focuses on the impact of a partial/full circular economy on material needs, energy consumptions and economics of the EU 27 chemical industry, including downstream value chains (e.g. automotive, packaging). It does not directly address GHG emissions but looks at enhancing circularity in the EU's chemical sector and models. The roadmap develops five linked scenarios or 'Loops' with increasing levels of materials circularity. Together they can bring 66 Mt of chemicals (out of a total of 106 Mt) back in circulation, but would require an additional 509 TeraWatt Hours (TWh) of energy and CAPEX between EUR 160-280 Bn. However lesser production of virgin chemicals would save around 250 TWh of energy.

Loop 1 involves the substitution (to a certain extent) of fossil feedstocks with renewable feedstocks such as biomass which in turn would require investment into new feedstock infrastructure and conversion assets. However, given biomass' low energy intensity compared to fossil resource, production would require 14% of total European agrarian land rendering the scenario a non-standalone option. It results in 12 Mt looped chemicals in a full circular economy, requires 0.03 Million Tonnes of Oil Equivalent (Mtoe) and 0.30 TWh of energy and CAPEX between EUR 20-40 Bn. Loop 2 scenario focuses on new products and solutions that can essentially be re-used "as is". It results in 17 Mt looped chemicals in a full circular economy. Loop 3 implies re-using existing materials without modifying their chemical bonds. It results in 19 Mt looped chemicals in a full circular economy, requiring 12 Mtoe and 135 TWh of energy and CAPEX between EUR 30-80 Bn. Loop 4 scenario suggests molecular bond modification to recover hydrocarbons and would require industry investment in further R&D (in cracking and gasification processes) and large scale assets. It results in 8 Mt looped chemicals in a full circular economy, requires 3 Mtoe and 40 TWh of energy and CAPEX between EUR 10-20 Bn. Loop 5 scenario involves molecular energy recovery, capture and reconstruction of new chemical feedstocks, new assets for creating dense CO2 sources and for the re-synthesizing of carbon into hydrocarbons and the establishment of H2 supply at scale. It results in 10 Mt looped chemicals in a full circular economy, requires 29 Mtoe and 334 TWh of energy and has CAPEX between EUR 100-140 Bn.

The roadmap does not make policy recommendations but advises European chemical companies to 1) gain greater knowledge of circular economy growth potential and shift capital and operating expenses accordingly, 2) shift focus from volume to value, 3) explore new business models, 4) increase resilience and deepen integration with customer value chains and 5) decrease dependence on oil and gas. An important consequence highlighted by the roadmap is the shrink effect on fossil-based feedstock and basic chemicals due to extensive re-use of molecules.

- Ecofys & Berenschot (2018)

The roadmap focuses on the Dutch chemicals sector - scope 1, 2 and 3 - and targets 80-95% emission reduction compared to 1990 (constructed baseline - 58 Mt CO2-eq) by 2050 (60-70 Mt CO2-eq reduction in absolute terms) and an intermediary target of 49% by 2030 (15 Mt CO2-eq reduction). Between 2030-2050, the remaining 56 Mt CO2-eq consists of end-of life emissions (38 Mt CO2-eq) and energetic and non-GHG emissions (18 Mt CO2-eq).

The Roadmap proposes six solution themes: closure of the materials chain (or circularity), alternative feedstock, energy efficiency, renewable energy, CCS, and sustainable products. From them, it explores thematic three transition pathways each targeting 80-95% GHG and energy-related emissions in a value-chain approach: Circular & Biobased pathway, Electrification pathway and CCS pathway. From these three transition pathways, the Roadmap develops two combination transition pathways that pick up the best elements while avoiding the extremes: 'Pathway 1: 2030 compliance at least costs' and 'Pathway 2: direct action and highvalue applications'. Both pathways aim at 49% of energy and other GHG emission reductions in 2030 and all GHG emissions by 80-95% in 2050. In Pathway 1, all emissions are reduced by 14% in 2030 and 95% in 2050. It aims to achieve the 2030 target at the lowest cost for the chemical industry. In Pathway 2, all emissions are reduced by 25% in 2030 and 95% in 2050. It is a more balanced approach which starts with reducing end-of-life emissions up to 2030, whilst using energy and feedstock resources optimally. In both pathways, energy efficiency improves at 1%/year after 2005, implying 22% improvement in 2030 and 36% in 2050. However, while end of life emissions are reduced by 25% by 2030 in Pathway 1, they are reduced by 1% in 2030 in Pathway 2 (93% by 2050 in both). Investment costs are also the same in both pathways (EUR 16 Bn in the chemical industry, and EUR 25 Bn outside the chemical industry).

The roadmap develops detailed technological options for each of the six solution themes, three transition pathways and two combination pathways. Circularity includes reuse, mechanical recycling (recycling of polymers, rubbers and other organics and of inorganic material through ground water filtration), and chemical recycling (Solvolysis, Pyrolysis, Low Temperature Gasification, High Temperature Gasification). Alternative feedstocks include bio-based feedstocks (Fermentation, Transesterification, Gasification and Pyrolysis) and H2 (through Alkaline electrolysis, PEM electrolysis and High-temperature solid-oxide electrolysis). Energy efficiency can be achieved through process intensification and efficiency as well as electrification with high COP technologies (such as Mechanical Vapour Recompression and high temperature heat pumps). Renewable energy includes renewable electricity and renewable heat (electric and hybrid boilers, biomass, geothermal energy). CCS with a potential to capture 14 Mt CO2/year includes pre and post combustion capture and oxy-fuel combustion.

The Circular & Biobased pathway involves the use of 700 PJ of sustainable biomass in 2050 with 2050 Investment Costs of EUR 24.5 Bn mainly for alternative feedstocks and EUR 10.1 Bn for the energy sector. The Electrification pathway relies largely on H2 from electrolysis in combination with CCU as alternative feedstock (requiring around 980 PJ of electricity or around 62 GW of offshore wind development) and costs EUR 91.3 Bn mainly for electrolysis and EUR 152.4 Bn for the energy sector - offshore wind capacity and related infrastructure costs. The CCS pathway relies overwhelmingly on CCS to mitigate around 11.4 Mt CO2/year with minimal deployment of other solutions (2.3 Mt for mechanical recycling, 0.5% per year energy efficiency improvement and 2.3 Mt reduction from functionality driven bio-based feedstock). The pathway costs up to EUR 12.4 Bn Eur for abatements for energetic and other GHG emissions and EUR 15.9 Bn for CCS (waste incinerators).

The roadmap develops a detailed analysis of the two combination pathways' technological inputs. In Pathway 1, there is heavy reliance on heat from bio-based boilers (requiring 70 PJ of biomass by 2030 and 435 PJ by 2050), followed by energy efficiency measures and mechanical recycling. Renewable energy comes from electric boilers (0 PJ in 2030 and 65 PJ in 2050) and biomass boilers (26 PJ in 2030 and 67 PJ in 2050). After 2030, the focus will be on closing the material loop with both mechanical and chemical recycling while functional bio-based materials will be implemented to the full potential. Further reduction of feedstock related emissions will be achieved by making bio-diesel and producing plastics. CCS will employed after 2030 and by 2050 will capture 2.4 Mt CO2 of process emissions and 1.2 Mt CO2 of energy-related emissions while waste incineration with 85% efficiency will capture 8.5 Mt CO2. Total CAPEX would be EUR 16 Bn investments in the chemical sector, and EUR 25 Bn investments outside the chemical industry. OPEX would be EUR 10 Bn/year for energy and feedstock

In Pathway 2, the maximum amount of biomass is 140 PJ in 2030 and 280 PJ in 2050. Biomass is first used for the highest value applications. Functional bio-based materials will be implemented to the full potential is this pathway and the remainder of the biomass will be used for the production of BTX and bioplastics. Circularity is maximized and CCU is implemented to its full potential. Methanol, and part of C2/C3, are produced on the basis of H2 (in combination with CCU); the total electricity use is 170 PJ or 11.4 GW off shore wind. The rate of energy-efficiency improvement is set at 1% a year. Maximum heat is sourced from geothermal sources, with the remaining demand provided by electrical boilers. The pathway omits the use of bio-based boilers. CCS will be used to capture 0.82 Mt CO2 by 2030 and 2.4 Mt CO2 by 2050 of process emissions and 5.1 Mt CO2 of energy-related emissions by while waste incineration will capture 8.5 Mt CO2 by 2050. The pathway requires additional 600 Kilo Tonnes (Kt) of H2 by 2050. Total CAPEX would be EUR 27 Bn investments in the chemical sector, and EUR 37 Bn outside the chemical industry. However, OPEX for Pathway 2 (EUR 9 Bn/year for energy and feedstock) would be lesser by 1 Bn/yr in 2050.

Cost-effectiveness of the abatement measures only includes investments cost and energy and feedstock OPEX based on current prices. The roadmap uses the Energy Transition Model (ETM). As a basis for parameters outside the chemical sector, the 95% scenario for 2050 made for the Raad voor de Leefomgeving (RLI, 2015) was used. Demand side and circularity play an important role in the roadmap. Industrial symbiosis too has been addressed in detail with the following sector: agrifood, transport sector, power sector, industry, and residential and tertiary sector; representing a potential of 50 Mt CO2/annum avoided emissions in 2030. New business models have not been identified but certain pathways are more conducive to their development.

The Roadmap makes the following policy recommendations: large-scale access to affordable and reliable renewable energy carriers, closing of carbon loops, introduction of renewable sources of carbon, an effective global carbon price in the longer term, coherent and wide-scale implementation of existing and innovative solutions, underscoring infrastructure, active cooperation between government and industry leadership, and creation of a stable policy framework with targets and support for a longer timeframe aligned with EU and where possible global initiatives.

- VCI (2019)

The roadmap's scope is limited to Germany (6 chemicals) with three decarbonization scenarios by 2050 developed with 1990 as a baseline Reference Pathway, Technology Pathway and Greenhous Gas Neutrality Pathway. The Reference Pathway targets 80% emissions reduction (emitting 812.1MtCO2 by 2050) amidst current investment level of EUR 7 Bn per year 0, requiring 54TWh electricty rper year. The Technology Pathway targets 95% emissions reductions (emitting 44.4 MtCO2 by 2050) requiring EUR 15 Bn additional investments and 224 TWh electricty required per year from 2040. In the Greenhouse Gas Neutrality Pathway, the industry decarbonizes 100% (emitting 0.0 MtCO2) by 2050 requring 628 TWh electricty required per year as of the mid-2030's and EUR 45 Bn additional investments.

The technology portfolio includes:

- ELECTRICITY-BASED PROCESSES
  - Methanol from electrolytic hydrogen and CO2
  - Ammonia and urea from electrolytic H2 and CO2
  - Electrically heated cracking
  - Electrically heated steam reforming
  - Synthetic naphtha/methane from electrolytic H2 and CO2
- ALTERNATIVE RAW MATERIALS/PROCESSES
  - Chemical recycling of plastics (pyrolysis, gasification, depolymerization)
  - Thermo-catalytic biomass conversion into BTX
  - Synthetic naphtha/methane from biomass
  - Co-firing with biomass
  - Methane pyrolysis
- DOWNSTREAM PROCESSES
  - Ethylene/propylene via methanol-to-olefins (MtO)
  - BTX via methanol-to-aromatics (MtA)
  - Olefins from synthetic naphtha and cracking
  - Olefins from synthetic methane + oxidative coupling of methane

Key assumptions are made: 1) electricity cost assumption: EUR 0.04 per kWh including levies and taxes, 2) a small volume of emissions remains which must be reduced using additional technologies and was not part of the study, 3) availability of affordable renewable electricity, 4) to achieve greenhouse gas neutrality the annual electricity requirements of the chemical industry would increase to more than eleven times (628 TWh) the current amount (54 TWh), 5) support for new technologies - their launch on the market can be sped up with state subsidies for investments. The roadmap also sketches a policy framework: 1) cheap raw material costs, 2) new technologies must be recognized as progress in regulations, 3) international climate protection agreement to prevent carbon leakage, 4) obstacles to the use and generation of renewable energies in industry must be removed.

- Agora Energiewende and Wuppertal Institute (2019)

The roadmap develops two pathways for the German chemical industry by 2050 with 2018 as a baseline. The 2030 pathway targets 51% emissions reductions (or 56 MtCO2 from 2018) by 2050 requiring 59% investment. The 2050 pathway targets 95% emissions reductions (or 192 MtCO2 from 2018) by 2050. The technological pathway includes Heat and steam generation from power-to-heat (from 2020), CO_2 capture at combined heat and power plants (between 2035 – 2045), Green hydrogen from renewable energies (between 2025 – 2035), Methanol-to-olefin/-aromatics-route (by 2025 – 2030), Chemical recycling (by 2025 – 2030) and Electric steam crackers (from 2035 – 2045).

Key assumptions include: 1) long-term, cross-party assurance that Germany will ensure internationallycompetitive energy prices, 2) a new version of the EU state aid guidelines must be geared towards climate neutrality, 3) Ten policy instruments: Carbon price floor with border carbon adjustment, Carbon Contract for Difference (CfD), Green financing instruments, Climate surcharge on end products, Carbon price on end products, Green public procurement, Quota for low-carbon materials, Green hydrogen quota, Changes in construction and product standards, Standards for recyclable products, 4) High carbon price in the EU ETS, coupled with a border carbon adjustment. The policy mix required by the roadmap includes: electricity costs of 60 euros/MWh, green hydrogen quota - target of at least ten gigawatts of electrolyser capacity in Germany by 2030, necessary infrastructure, including that required for hydrogen production and transport, carbon capture and storage (CCS) or the transport of large quantities of electricity.

- Material Economics (2019)

The roadmap develops three 2050 net-0 pathways or -173 MtCO2 for European chemicals (plastic) industry with 2015 as a baseline: New Process Pathways, Circular Economy Pathway, and Carbon Capture Pathway. Emission reductions in the New Process Pathway are split along materials efficiency and circular business models - 29 MtCO2/Yr, materials recirculation and substitution - 111 MtCO2/Yr, new processes - 60 MtCO2/Yr. In this pathway, plastics produced per year come from the following routes: circular economy in major value chains - 14%, mechanical recycling - 13%, bio-based production - 33%, chemical recycling (incl. steam cracking) - 40%. The energy mix is calculated at: materials efficiency and recirculation - 0.8 EJ/Yr, more efficient processes - 0.5 EJ/Yr, electricity - 1.2 , EJ/Yr biomass - 1.2 EJ/Yr, end-of-life plastics - 1.9 EJ/Yr. The Circular Economy Pathway sees emissions reductions split along materials efficiency and circular business models - 54 MtCO2/Yr, materials recirculation and substitution - 105 MtCO2/Yr, new processes - 40 MtCO2/Yr. In this pathway, plastics produced per year come from the following routes: circular economy in major value chains - 27%, mechanical recycling - 18%, bio-based production - 27%, chemical recycling (incl. steam cracking) - 28%. The energy mix is calculated at: materials efficiency and recirculation - 1.5 EJ/Yr, more efficient processes - 0.5 EJ/Yr, electricity - 0.9 EJ/Yr, biomasS - 1 EJ/Yr, end-of-life plastics - 1.6 EJ/Yr.

In the Carbon Capture Pathway, emissions reductions are split along materials efficiency and circular business models - 29 MtCO2/Yr, MATERIALS RECIRCULATION AND SUBSTITUTION - 51 MtCO2/Yr, new processes - 61 MtCO2/Yr, carbon capture and storage - 59 MtCO2/Yr. In this pathway, plastics produced per year come from the following routes: circular economy in major value chains - 14%, mechanical recycling - 13%, bio based production - 28%, chemical recycling (incl. steam cracking) - 12%, electric steam cracking with ccs - 16%, steam cracking with ccs - 16%. The energy mix is calculated at: MATERIALS EFFICIENCY AND RECIRCULATION - 0.8 EJ/Yr, more efficient processes - 0.1 EJ/Yr, fossil fuels - 1.5 EJ/Yr, electricity - .2 EJ/Yr, biomass - , end-of-life plastics - .9 EJ/Yr. For all the three pathways, the cost breakdown of technologies eur per tonne plastics (Capex in brackets) are: Steam Cracking - 1242 (134), Mechanical Recyling - 609 (102), Steam Cracking + CCS & EoL CCS - 1492 (191) Electric Steam Cracking + EoL CCS - 1653 (220) , Biobased Feedstock - 1822 (338), Chemical Recyling - 1720 (402), Material Efficiency and Circularity – 1377. Investment in plastics production capacity increases by 199% for the New Process Pathways, 158% for the Circular Economy Pathway, and 122% for the Carbon Capture Pathway.

The technology portfolio is broad. It includes

- NEW AND IMPROVED PROCESSES
  - Shifting production processes and feedstocks to eliminate fossil CO2 emissions,
- CLEAN UP CURRENT PROCESSES:
  - Increase process- and energy-efficiency (steam crackers)
  - Switch to lower-CO2 fuels and electricity
  - Increased use of lighter feedstock
- NEW PROCESSES AND FEEDSTOCKS
  - Plastics from bio-feedstock
  - Chemicals recycling of end-of-life plastics (depolymerisation, solvolysis, pyrolysis + steam cracking, gasification) Reprocessing of by-products (e.g., through methanol-to-olefins)
  - New polymers and catalysts
- ELECTRIFICATION
  - Electrification of steam crackers
  - Electrification of cooling, heating, compression, and steam
  - Electrification of hydrogen production
- CARBON CAPTURE
  - Capture and permanent storage of CO2 from production and end-of-life treatment of materials, or use of captured CO2 in industrial processes

- CARBON CAPTURE AND STORAGE
    - Carbon capture and storage (CCS) on steam cracker furnaces and refinery processes
    - CCS on waste-to-energy plants
- CARBON CAPTURE AND UTILISATION
    - Synthetic chemistry' to produce new chemicals from CO2 ('power to X') using non-fossil sources of carbon

Chemical recycling of end-of-life plastics occur through two representative routes : Gassification [Input: Plastic waste 1.1t, Electricity 1.4 Mwh, Hydrogen 0.2t, Output: Plastics (HVCs) 1t, CO2-emission 0.2t], Pyrolysis and Steam Cracking [Input: Plastic waste 1.1t, Electricity 6.9 Mwh, Hydrogen 0, Output: Plastics (HVCs) 1t, CO2-emission 0.3t]. Between 20 and 24 Mt of plastics are derived from bio-feedstock in 2050. Bio-based plastics production with methanol as a new platform chemical occur through Anaerobic Digestion [Input: Dry Biomass 1.9t, Electricity 1.4 Mwh, Hydrogen 0.3t, Output: Plastics (HVCs) 1t], and Gassification [Input: INPUT Dry Biomass 3.5t, Electricity 1.4Mwh, Output: Plastics (HVCs) 1t]. Overall, CCS leads to emissions cuts of 59 Mt CO2 per year.

Key assumptions per pathway are made. Overall, it is assumed that production increases 15%, from 62 Mt in 2015 to 71 Mt per year in 2050, while emissions rise from 173 MtCO2 in 2015 to 192 MtCO2 in 2050. In the New Process Pathway - 62 percent of production from end-of-life plastics by 2050 occur through a combination of mechanical and chemical recycling, hinging on a signicant increase in collection rates of end-of-life plastics. Remaining 38 percent of production from biomass feedstock, using methanol as new platform chemical. Increased reliance on electricity for hydrogen production and in production processes. In the Circular Economy Pathway, the emphasis on demand-side opportunities for materials efficiency, materials substitution and new circular business models for plastics, result in the decreased production volume to 52Mt by 2050. In the highly circular scenario, 62 percent of plastics is produced through mechanical and chemical recycling while the remaining 38 percent comes from biomass feedstock. In the Carbon Capture Pathway, the emphasis is on using CCS/U on plastics production from fossil feedstocks as well as CCS on end-of-life incineration, and electrication of steam crackers to reduce direct emissions. 32 percent of production comes from biomass feedstock to enable o-sets from incomplete fossil CO2 capture through capture of biogenic CO2 from incineration of bio-based plastics.

- McKinsey & Company (2018).

The roadmap focuses on the Dutch industrial sector and develops six decarbonisation measures and three scenarios (from a combination of the six decarbonisation measures) for the sector to lower its CO2 emissions by 60% by 2040 and by 80% and 95% by 2050 (with baseline 1990 emissions 45 Mt direct and 22 Mt indirect). The six decarbonisation measures are: 'Energy efficiency', 'Electrification of heat demand', 'Change of feedstock', 'Develop routes to reuse and recycle materials', 'Decide on steel production route(s)', 'Develop CCS/U'. The scenarios as of 2014 are: 'Cheaper route: 60% reduction until 2040', 'Steeper route: 80% reduction until 2040', and 'Steeper route: 95% reduction until 2050'. This reduction can in theory be achieved without reducing industrial output, by creating, refining, and applying new processes, technologies, and feedstocks on a large scale. As a reference scenario, the roadmap finds that the BAU scenario would lead to -40% (ref 1990) until 2030, but with no significant reductions after that.

The six decarbonisation measures combined offer a mitigation of 20 Mt CO2 in the 60% scenario, 36 Mt CO2 in the 80% scenario and 46 Mt CO2 in the 95% scenario. Although electrification of heat demand and development of CCS/U capabilities are the two most significant options, the roadmap recommends a combination of all six options as the most economically beneficial. This combination would increase the electricity demand by 215 PJ (renewable power supply expanded by 6 Gigawatts (GW) to 64 GW), and cost between EUR 21-23 Bn by 2040 for the 60% scenario with a viable business case for only about 20% investments while 80% would have a negative payback at current commodity and technology prices. In the 80% scenario, the cost would rise to about EUR 55 Bn by 2050 and in the 95% scenario, the cost would be as high as EUR 71 Bn until 2050. Implementation of a different selection of options could increase CAPEX further. The main factor dictating the relative contributions of the six different options is the pricing of electricity (base and peak pricing), especially with regards to the business case.

The 60% scenario implies energy demand (including feedstock) be reduced by 12% while direct CO2 emissions be reduced by 46%. The scenario also implies industrial indirect CO2 emissions to increase by 11 Mt CO2 by 2040 unless an 80% renewable energy supply is available. The 80% scenario implies industry energy demand (including feedstock) reduced by 17% and industrial direct CO2 emissions reduced by 74%. The 80% and 95% scenarios will have implications like a shift from fossil-based electricity generation to renewables (from 16 Mt CO2-eq to 0-6 Mt CO2-eq), electrification of industry amidst growing electricity demand (up to 560 PJ in 2040 including an additional 6 GW renewable energy and other sources such H2), and future electricity price.

The main factors determining the relative contributions from each option on each scenario were the future price of energy (most influential factor), commodity prices, equipment costs and the extent to which industrial companies pursue other priorities. Under each scenario, the key parameters taken into account were: CO2 emissions (direct and indirect) per industrial sector, energy source per sector and correlated CO2 emissions, regional mapping clusters of emissions and energy demand. The roadmap scenarios clearly distinguish between efficiency improvements, system developments and technological innovations. Demand side measures focus strongly on circular economy (reuse, remanufacturing and recycling) influenced by the 'Nederland circulair in 2050'. Two of the six decarbonisation measures directly involve circularity: 'Develop routes to reuse and recycle materials' (mitigation potential of 1 Mt CO2) and 'Develop CCS/U' (mitigation potential of 3 Mt CO2).

The roadmap lists three key policy recommendations: develop a master plan for decarbonisation, optimise planning for long-term economic value, and structure public incentives to support the master plan.

Studies

- Cefic & Oxford Economics (2015)

The study focuses on the European chemicals industry framed amidst a declining share of the Europe-based chemicals industry in global sales due to declining competitiveness. According to the report, the sector faces additional pressure rom inside the EU in the form of highly ambitious environmental, health and climate regulation accelerating deterioration of industrial competitiveness and outside from the US shale gasboom. (which has increased US chemical producers competitiveness). The report recommends measures which could potentially halt the decline of chemical export market share, adding EUR 35 billion to EU GDP and creating more than half a million new jobs over the next 15 years. These include: (1) co-ordinated, competitive energy policy, (2) responsible climate policy, (3) innovation policy, (4) regulatory stability and consistency, (5) open markets, (6) access to raw materials, (7) addressing skills and people mobility, (8) first class logistics.

- Ecofys (2015)

The Ecofys 2015 study focuses on the European fetilizers sector (limited to two key fertilisers Ammonium nitrate (AN) and Urea) with a 2050 perspective. It estimates that for (incremental) reduction in GHGs in ammonia production there is a need for improvements in the reformer section, application of low-pressure synthesis, improved process control, process integration and motors. BTTs are also needed but are unlikely to be implemented before 2050. The rapid development of the hydrogen economy could change things significantly but will need policy to stimulate demand side management. For reduction in GHGs in nitric acid production, the report recommends the use of waste heat. It recommendations: (1) the design of carbon market and climate policies post-2020, (2) implementation of demand-side management and CCS, regulation to promote best farming practices. The technology portfolio includes CCS/CCU, Hydrogen, Syngas produced from biomass, Electrolysis, Nuclear high-temperature electolysis, and closing the fertilizer loop'- efficient use of on-farm waste and nutrient recycling strategies.

- VCI (2017)

The VCI study focuses on chemistry 4.0 and analyses 30 trends important to the German chemicals industry. It concludes that many innovations will be incremental but a large amount of change will also be disruptive -several linked to digitalization of business models and many linked to sustainability and circular economy. The implications of digitalisation are expected efficiency gains: R&D (30%), purchasing (5%), logistics (20%), manufacturing (15%), sales & marketing (40%), administration (40%). The chemicals industry's key role in the circuar economy is explored through 7 levers: (Re)Design, Resource efficient and climate friendly production, Return, Recycling, Recovery of energy, Residue depositing, Remove. Recommended actions for companies and their associations include: (1) set strategic goals,(2) enhance resources, (3) seize opportunities, (4) Transform corporate culture. Recommended political and regulatory conditions include: (1) support digital education, (2) expand technical infrastructure, improve data security, review data and protection rules, (3) Promote cooperation and unbureaucratic development of platforms, (4) initiate dialogue on the necessity of and perspectives on digitilisation, (5) understand circular economy as an integrated and open approach, (6) raise public awareness, (7) expand innovation support, (8) review regulatory framework.

The technological portfolio includes process technologies (biotechnology and utilisation of RE - application of biological raw materials in production processes (biologization of chemistry)), production of chemicals from electricity, hydrogen, and CO2, change in product portfolios (e.g. around electric engines such as battery technology and battery recycling, lightweight materials), use of big data and advanced methods of analysis for decision making (e.g. predictive maintenance, networked logistics, and the application of concepts from virtual reality and advanced simulation ('in-silico') for research), and the automation of manufacturing processes.

- UK Department for Business, Energy and Industrial Strategy (2017)

The strategy forms part of the UK Industrial Decarbonisation and Energy Efficiency Roadmaps project, a key collaboration between Government and industry to help industry make the low carbon transition while also maintaining its competitiveness. This strategy identifies 10 concrete actions to enable the chemicals sector to decarbonise and improve its energy efficiency. These are: 1) Strategy, Leadership and Organisation, 2) increase clustering, industrial symbiosis and resource efficiency, 3) identify and implement industrial Waste Heat Recovery projects, 4) Identify and deliver opportunities for embedded generation, demand side response and energy storage, 5) support development, scale-up and awareness raising of key innovative decarbonisation and energy efficiency technologies, 6) encourage greater use of sustainable biomass/biogenic material including waste as chemicals feedstock and energy to deliver a competitive and lower carbon footprint within the chemicals sector, 7) develop and implement a strategy to integrate smarter use of energy and feedstocks in the chemical sector with Industrial Carbon Capture, Usage and Storage (CCUS), 8) increase skills and knowledge within the sector to enable a low carbon competitive future for the chemicals industry, 9) support access to finance for mature energy efficiency and decarbonisation-related investments, 10) increase research, development and demonstration (RD&D) with potential applications for energy efficiency and decarbonisation in the chemical sector.

The industry believes that this action plan compliments yheir strategy well. Firstly, because reducing their sites' GHG emissions is a supporting priority to the growth vision. And secondly, because their main growth priorities: securing competitive energy for use as a fuel and a feedstock (raw material), accelerating innovation, and rebuilding supply chains, also align with many of the tasks in the plan. For example: increased use of bio-resources, waste and captured carbon as a feedstock, clustering, and the development and scale-up of innovative decarbonisation and energy efficiency technologies. Indeed, the latter is expected to be an enabler for climate solutions in other sectors – thereby adding to the energy saving solutions the chemical sector already provides to the UK's homes and its energy, transport and agricultural sectors.

- Climate Strategies and DIW Berlin (2018)

This study focuses on the basic materials industry and puts forward a portfolio of seven major mitigation options. These include: Share, Repair and Reuse. More and Purer Recycling, Material Efficient Design of Products, Efficient Manufacturing, Material Substitution, Low-Carbon Processes, Reduce Plant Emissions. It highlights an array of policy instruments for unlocking these mitigation options – including existing and not-yet existing tools. These include: LCA Labels, Eco design, Standards, Disclosure in Financial Reporting, Environmental Management Systems, Advice, Training, Networks, Green Public Procurement, Waste Charge, Consumption Charge, Innovation Support, Current ETS, Cfd, Infrastructure. The study then discusses criteria for prioritizing policy instruments: first, prioritize instruments that support multiple mitigation option, second, prioritize instruments that align private choices with long-term policy objectives, third, prioritize instruments that are complementary, fourth, prioritize policy and experimentation in individual Member States.

- Wyns, T., Khandekar, G., Robson, I. (2018)

The study focuses on 11 energy intensive sectors - iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferro- alloys and silicon, pulp and paper, ceramics, lime, and glass – as their input to the European Commission's Strategy for long-term EU greenhouse gas emissions reductions. With 2015 as a baseline, the report catalogues the emissions and energy profile of the 11 EII. It highlights the constructive and solutions-oriented role that the EIIs have been playing, determines a combination of possible key solutions that will help EIIs to significantly reduce their emissions, as well as stress the need to address the necessary conditions to ensure that Europe is at the forefront of the energy and industrial transformation.

The study provides an in-depth analysis of 9 key pathways applicable to most industries. These include: Further energy efficiency improvements and energy savings, Process integration, Further electrification of heat, Further electrification of processes, Use of low-CO2 hydrogen, Valorisation of CO2 (Carbon Capture and Utilisation), Use of biomass, Carbon Capture and Storage, and Higher valorisation of waste streams and materials efficiency. It identifies six main categories of key framework conditions: R&D challenges, Securing adequate and competitively priced low-CO2 electricity supply, Infrastructure needs, Financing challenges, Conditions for enhanced circularity and materials efficiency, and Regulatory challenges. It then provides a 9-point regulatory framework to ensure that EIIs successfully transition to a low-CO2 economy while maintaining basic materials production, which is essential to all and in particular green value chains, in Europe:1) Protection against unfair international competition towards a level playing field, 2) Full carbon leakage protection from both direct and indirect costs of the EU ETS, 3) A large and ambitious mission oriented RD&I program for industrial low-CO2 technologies, including funding for industrial demonstration and scale up, 4) Competitively priced, carbon-neutral energy, 5) Consistency within the energy and climate policy framework to ensure that energy consumption and low-carbon policies are compatible, 6) Reconsideration and a better alignment of the environmental state aid guidance, 7) Industrial symbiosis and a circular economy through the effective combination of energy recovery and recycling, 8) Streamlining of the permitting procedures allowing a timely and predictable set of infrastructures and interconnections, and 9) Transparent accounting framework for CCU across sectors and value-chains to allow business cases to emerge.

- Suschem (2019)

The SusChem SIRA report focuses on technology priorities towards 2030, across Advanced Materials, Advanced Processes as well as the implementation and co-development of Enabling Digital Technologies. Horizontal topics are equally addressed, including sustainability assessment innovation, safe-by-design for chemicals and materials, as well as building on education and skills capacity in Europe.

The new strategic document highlights the role of the chemical industry in boosting innovation in Europe and the potential for sustainable chemistry technologies to tackle societal challenges, as outlined in the European Commission's Research Framework Programme Horizon 2020.

The SIRA is organised around five of the seven key societal challenges described in Horizon 2020 and highlights a portfolio of potential sustainable chemistry solutions.

- Climate action, resource efficiency and raw materials (SC5) addressing issues around the circular economy, raw materials and feedstock, water and waste management, resource and energy efficiency, and process intensification for the chemical plant of the future.
- Food security, sustainable agriculture and the bioeconomy(SC2) contributing solutions along the full bioeconomy value chain from planting to new biobased products and fuels.
- Secure, clean and efficient energy (SC3) shows benefits for energy efficiency gains (due particularly to new materials) within industry and in wider society and contributes to low carbon energy production and advanced energy storage technologies.
- Health, demographic change and wellbeing (SC1) illustrates SusChem's potential to enable personalised healthcare and advanced diagnostic techniques.
- Smart, green and integrated transport (SC4) shows how sustainable chemistry will contribute to greener vehicles providing mobility with low or no emissions.

Two further SIRA chapters cover Information and Communication Technologies (ICT), describing how more sustainable processes can be enabled by ICT and how sustainable chemistry itself enables advances in ICT, and Horizontal Issues illustrating SusChem's ambitions to build skills capacity, better assess sustainability in manufacturing, address issues of societal uptake of technologies, and promote innovative business models.

This report has been analysed more deeply in the technology section (Chapter 9).

- Wyns, T., Khandekar, G., Axelson, M., Sartor, O., Neuhoff, K. (2019)

This report builds upon the growing momentum for an EU industrial transition to net-zero amongst policy makers and even industry, and sketches the blueprint of such an industrial strategy towards climate neutrality. The policy-side twin of the IT50 Material Economics-led research, this report identified policy options to address key challenges industry faces on the transition path to climate neutrality. It also indicates how this policy set can be integrated into an industrial strategy and what governance instruments could guide to a successful implementation. This report focuses on the European basic materials industries and related value chains, with a specific focus on the iron and steel, cement, and chemicals sectors.

This report considers six main challenges to a climate-neutral industry: 1) Innovation gaps from basic R&D towards the deployment of new technologies, 2) An insufficient circular and materials efficient economy, 3) Barriers to market entry for low-CO2 solutions, 4) Lack of streamlining between the energy and industrial transition to climate neutrality and infrastructure needs for the transition, 5) Possible bottlenecks in scaling up investments and the risk of high-carbon lock-ins and 6) The complexity of integrating different types of policy instruments, policy areas and competences into a cohesive (industrial) strategy.

The report then puts forth 6 overarching and nearly 70 specific instruments to address the transition challenges: Innovation framework for a climate neutral industry, An enhanced circular economy package for basic materials, Creating competitive lead markets for low-CO2 solutions, Aligning the energy and industry transition and enabling infrastructure for industrial transition, Scaling up investments and avoiding high-carbon lock-in, Designing an industrial strategy for climate neutrality.

12.1.2 Refining Sector

Roadmaps

- Concawe (2018)

The study focuses on the EU refining sector (Scope 1 and 2 emissions) and develops two scenarios (baselines unclear): 2030 and 2050, wherein via a combination of three technological options, emissions can be reduced between 20-30% and up to 70% respectively. The three options adopted via

a top-down approach include: 'Energy Efficiency (EE)', 'Use of Low-carbon Energy Sources (LCE)', and 'CO2 Capture (CC)'.
The EE option comprises refinery process efficiency (continuous improvement through implementation of a combination of measures and small projects for example catalyst improvements and hardware improvements; major capital projects which provide larger efficiency improvements for example new process plants; and Inter-unit heat integration), energy management systems (which combine equipment with strategic planning, organisation and culture), and increased recovery of refinery low-grade heat for export and electricity production.

The LCE option encompasses benefits arising from decarbonisation of the gas and electricity grid, reduction of liquid fuel burning, improved recovery of H2 and LPG from fuel gas, and increased use of imported low-carbon electricity (which includes a partial replacement of own generation by imported low-carbon electricity, increased use of electricity for general operations a/o rotating machines, substitution of fired heaters by electric heaters and production of H2 with electrolysers using imported renewable electricity). The CC option sees the capture of a portion of the total CO2 emitted by refineries. In the CC option, a combination of CCS and steam reforming plants (SMR) to produce low-carbon intensity H2 is explored.

The study assesses that by 2030, the bulk of the CO2 savings will stem from process energy efficiency and improvement measures while the impact of external opportunities becomes prominent only in the 2050 horizon. Achievable energy efficiency improvements are quantified at 0.7% per year on average by 2050 (15% by 2030, 25% by 2050). The study stresses that without CCS, total 2050 emission reductions would be 50% with a large degree of uncertainty surrounding CCS penetration. The study emphasizes that progressive availability of low-carbon electricity in the average EU mix (at affordable price for industrial users) could reduce EU refinery emissions up to 25% by 2050 (bringing the total electricity consumption of the sector close to 180 TWh/annum, or around 5% of European current electricity generation). The potential contribution of the recovery of low-grade heat to either internal production of electricity or export is deemed insignificant.

R&D is identified as a key enabler for technological development to make the potential a reality at reasonable pace within the time horizons (2030 and 2050). The study highlights multiple areas where cross-sectorial collaborative R&D may be required to accelerate the development and integration of technologies including green H2 and CCS. However, it warns that despite such collaborative R&D, refineries will need to attract investments to revamp existing or build new plant and required infrastructure to integrate the developing technologies which will necessitate a supporting regulatory framework and a favourable economic environment.

CAPEX is estimated at minimum EUR 40 Bn (generic cost of the different technologies and opportunities identified) with actual implementation costs variable per individual asset. The study assumes constant refining capacity in the EU at the 2030 level, when all options are exercised, different rates of deployment of technology, energy prices and the of degree of decarbonisation of the electricity grid.

Studies

- JRC IPTS (2015)

The study focuses on the EU refining sector and aims at a quantitative and qualitative assessment of impact of legislation on costs and revenues of the EU petroleum refining industry and therefore on its capacity to remain internationally competitive. It analyses how coherently and consistently the EU legislation for the sector works together, whether it is effective and efficient, and whether it is associated with excessive regulatory burdens, overlaps, gaps, inconsistencies or obsolete measures. The pieces of EU legislation studied were: • the Renewable Energy Directive, • the Energy Taxation Directive, • the EU Emissions Trading System, • the Fuel Quality Legislation, • the Directive on Clean and Energy-Efficient Vehicles, • the Industrial Emissions Directive (together with the Integrated Pollution Prevention and Control Directive (IPPCD) and the Large Combustion Plants Directive (LCPD), • the Strategic Oil Stocks Directive, • the Marine Fuels Directive, • the Energy Efficiency Directive, • the Air Quality Directive.

The main findings of the report were:
• Observed developments in EU-28 international competitiveness vis-à-vis main competing world regions
The 2000-2012 period shows a relative loss of competitiveness, as it puts pressure on the investment possibilities of the European refining sector, attributed to the relative increase in energy costs in EU refining. The effect of increasing energy prices adds to the effect of a regulation-related increase in energy consumption by the European refineries. In general, the international competitiveness of the bottom 50 % of EU refineries declined more than that of the top 50 %.

• Impact of EU legislation on investments in the EU refining industry
Some legislation packages have lead to sizable additional investments by refineries, some have lead to increased energy consumption and, thus, higher operating costs, while some have partially contributed to reducing refineries' utilisation rate (as indicated by OURSE modelling), which can negatively affect refineries' energy and operating efficiency.

• The impact of EU legislation on the competitiveness of EU refineries
The cumulative quantified cost impact per barrel of processed throughput from the investigated regulation packages is significant. The regulatory cost effect has been increasing from 2000 to 2008 and appears to stabilise afterwards until 2012. The identified cost impacts of regulation on refineries' performance primarily imply the diversion of revenues towards regulatory compliance investments and operating costs rather than making other investments and operation adjustments that improve competitiveness.

Has EU legislation affected EU refineries in a coherent manner? It has been observed that the effects of more horizontal (initially cross-industry) pieces of legislation (such as the Air Quality Directive and Energy Efficiency Directive) are likely to be implicitly covered within the impact of more focused regulation which establishes tangible norms and limits (such as, for example, the fuel quality legislation and Industrial Emissions legislation) which can be directly linked to particular changes in investment and operating expenditures. The efforts made by the EU refineries to meet the requirements of the Industrial Emissions legislation and Renewable Energy Directive during the analysed period have also contributed to meeting the objectives of the Air Quality Directive and Energy Efficiency Directive which do not address the refining sector specifically. In terms of general and focused regulations' objectives with regard to GHG emissions, the analysis shows that the requirements imposed by EU legislation that lead to increased energy consumption create tensions between the objectives of higher fuel quality and lower industrial emissions on one hand and the objectives of decreasing GHG emissions on the other (such as those specified in the EU Emissions Trading System and fuel quality legislation). At the same time it should be noted that the increasing energy costs create additional incentives for refineries to make efforts to improve their own energy efficiency, which is the main objective of the Energy Efficiency Directive.

- Concawe (2020)

This study is a detailed literature review of the efuel production technologies and implications in terms of efficiency, contribution to reductions in GHGs, technology readiness level, environmental impact, investment, costs and demand that could help to define a better picture of the potential role in decarbonisation of these fuels in Europe. The study notes that although e-fuels are not expected to play a significant role in meeting the transport sector demand in the short-term (2030), in the long term (2050) they scould contribute 30% of the expected transport demand in EU by 2050 (depending on a number of factors), mainly focused on aviation, maritime and long-haul road transport segments.

The study highlights the advantages of E-fuels, in particular, 1) their ability to achieve a significant CO2 reduction versus equivalent fossil-based fuels (CO2 abatement potential ≈ 85-96% on Well-To-Tank–WTT-basis or 70% LCA analysis), 2) their higher energy density compared to batteries which makes them ideal for no electricity-based usage sectors (e.g. aviation and shipping), 3) easier (and relatively inexpensive) storage and transport compared to electricity allowing to compensate seasonal supply fluctuations, 4) adaptability to existing infrastructure for transportation and storage, 5) given that some e-fuels are chemically pure hydrocarbon, they could be deployed immediately across the whole transport fleet without any major changes in engine design, 6) reduction of GHG emissions in both existing and new vehicles without requiring the renewal of the fleet, 7) possible 100% blending ratio when adding methane to natural gas, and e-liquid fuels to gasoline and diesel, 8) possibly positive environmental impacts given favourable combustion characteristics of the molecules produced.

However, they face numerous barriers such as need for a significant amount of new renewable energy, unexpected problems when scaling up the currently pilot-level technology, and high CAPEX for production and deployment. There are however some key enablers which could help e-fuels development and usage. These include: technical development and scale-up, high full load hours and energy storage, accessibility to affordable renewable energy prices, favourable regulatory and policy framework, greater industrial symbiosis, OEM (Original Equipment Manufacturer)-

Industry alliances, and new business models which could allow import of e-fuels from low-electricity price regions in the world allowing 20-50% cost reduction.

The report provides a detailed technology assessment. Its technology portfolio includes:

- Feedstock-related technologies
  - CO2 capture
    - Capture from biomass combustion
    - Capture from industrial processes (such as refineries) or power generation plants
    - Biogenic CO2 sources include biogas-upgrading plants, CO2 from ethanol plants, and CO2 from the combustion of biogas
    - Direct Air Capture (DAC)
      - Absorption + Electrodialysis
      - Absorption + Calcination
      - Adsorption/desorption (Temperature Swing Adsorption process (TSA)
    - CO2 purification
  - Hydrogen electrolysis
    - Alkaline Electrolysis (AEC)
    - PEM-electrolysis
    - High-temperature solid-oxide electrolysis (SOEC)
- E-fuels technologies
  - E-fuels conversion technologies
  - E-methane
    - Catalytic methanisation
    - Biological methanisation
  - E-Ammonia
  - E-Methanol
  - e-OME (oxymethylene ether) and e-DME (dimethyl ether)
  - Liquid e-fuels (e-gasoline, e-diesel, e-jet)
    - Via methanol synthesis
    - Via Fischer-Tropsch synthesis
    - Fischer-Tropsch versus methanol synthesis

12.1.3 Steel Sector

Roadmaps

- JRC (2012)

The roadmap focuses on the EU steel sector with 2010 as a baseline and 2030 as a target and develops three scenarios: Baseline scenario, Alternative scenario 1(AS1) with two variations: 2x-Fuel price and 5x-Fuel price (compared to BS scenario) and Alternative Scenario (AS2) with two variations of CO2 price: 100EUR -CO2 and 200EUR -CO2. The Baseline scenario sees a -14% emissions reduction by 2030. The Alternative scenario 1(AS1) estimates emissions reductions of -16% (for 2x-Fuel) and -21% (for 5x-Fuel). The Alternative Scenario (AS2) estimates emissions reductions of -15% (100EUR -CO2) and -19% (200EUR -CO2) by 2030. Key technologies include: Corex/Finex ironmaking, MIDREX, EnergIron/HYL, Direct Sheet

Plant (DSP), CCS, Top Gas Recycling Blast Furnance (Under ULCOS programme), HIsarna (Under ULCOS programme), ULCORED (Under ULCOS programme), ULCOWIN (Under ULCOS programme).

The roadmap makes the following assumptions: that EU steel demand will still be 8% lower in 2030 compared to 2007, EU steel exports will decline in future, from traditionally being a net exporter to becoming self-sufficient in steel by 2030, scrap requirements will increase, availability of home and prompt scrap is expected to decrease, the recovery of obsolete scrap is expected to fall and remain relatively low, scrap recovery rates are also expected to rise from their current 50% to 58%. Additionally, in the BS scenario, demand for steel and, prices of fuels and resources evolve according to the projection of the European Commission. In AS1 scenario, there is an increase of fuel and resource prices while in AS2 scenario, there is a variation in CO2 emission price. The roadmap also assumes that there will be no more than six retrofits for the integrated and secondary steel route per year.

- Eurofer (2014)

The roadmap focuses on the EU steel industry and develops four scenarios using 1990 and 2010 as baselines. It estimates that by 2050 the sector can achieve 63% decarbonisation compared to 1990 levels by combining all technologies that are currently under development, including CCS. Along the four scenarios – 'Economic Scenario', 'Theoretical-Maximum Abatement Scenario without CCS', 'Theoretical-Maximum Abatement Scenario With CCS' and 'Hypothetical Emission Reduction Scenario' relying on breakthrough technologies in combination with CCS – the roadmap envisages maximum CO2 emission reductions (between 2013-2050) of 13%, 38%, 57%, and 80% respectively.

The Economic Scenario is described as the one which achieves the best balance between emission reduction and economic viability. It assumes continued decarbonisation of the power sector, increased scrap availability, underscores sharing of best practices and the implementation of cost-effective incremental technologies. It requires, however, access to scrap and energy at competitive prices, incentives and full offset of distortive CO2 costs until an international level-playing field is restored. The Theoretical-Maximum Abatement Scenario without CCS is to be achieved by shifting from Blast Furnace – Blast Oxygen Furnace (BF-BOF) to DRI-EAF and requires that natural gas-based DRI becomes competitive in Europe. The Theoretical-Maximum Abatement Scenario with CCS can be achieved through the use of BF-Top Gas Recycling technology in combination with CCS and requires support for demonstration and deployment of BF-TGR, access to CCS widespread at competitive prices. The Hypothetical Emission Reduction Scenario' relying on breakthrough technologies in combination with CCS which aims for the highest CO2 reduction is largely based on circularity and implies industrial symbiosis but requires support for R&D, demonstration and deployment of breakthrough technologies.

The roadmap assesses that the highest emission reduction possible while maintaining economic viability is 0-15%. Higher emission reductions will result in uneconomic scenarios, given large investments in infrastructure and higher operating costs. The roadmap makes the following key assumptions: increased scrap availability (from 96 Mt in 2010 to 136 Mt in 2050), greater share of EAF steelmaking (44% by 2050), continuous decarbonisation of power sector, and continuous market growth (0.8% annually or 236 Mt EU crude steel production in 2050). Key technologies underscored are BF-TGR, ULCORED/HIsarna, CCS on all emission sources, Electrification of heating, H2-based reduction, and Electrolysis. A 14 point policy recommendations list envisages a strong role by the EU (policy support and coherence, trade shepherding, transparency and predictability, and global climate leadership), and underscores fairness, competitiveness, the need for differentiation, R&D support, energy prices, financial price stability, support for development and deployment of new technologies, CO2 sequestration into products, value chain approach, and circularity.

- McKinsey & Company (2014).

The roadmap focuses on the Dutch industrial sector and develops six decarbonisation measures and three scenarios (from a combination of the six decarbonisation measures) for the sector to lower its CO2 emissions by 60% by 2040 and by 80% and 95% by 2050 (with baseline 1990 emissions 45 Mt direct and 22 Mt indirect). The six decarbonisation measures are: 'Energy efficiency', 'Electrification of heat demand', 'Change of feedstock', 'Develop routes to reuse and recycle materials', 'Decide on steel production route(s)', 'Develop CCS/U'. The scenarios as of 2014 are: 'Cheaper route: 60% reduction until 2040', 'Steeper route: 80% reduction until 2040', and 'Steeper route: 95% reduction until 2050'. This reduction can in theory be achieved without reducing industrial output, by creating, refining, and applying new processes, technologies, and feedstocks on a large scale. As a reference scenario, the roadmap finds that the BAU scenario would lead to -40% (ref 1990) until 2030, but with no significant reductions after that.

The six decarbonisation measures combined offer a mitigation of 20 Mt CO2 in the 60% scenario, 36 Mt CO2 in the 80% scenario and 46 Mt CO2 in the 95% scenario. Although electrification of heat demand and development of CCS/U capabilities are the two most significant options, the roadmap recommends a combination of all six options as the most economically beneficial. This combination would increase the electricity demand by 215 PJ (renewable power supply expanded by 6 Gigawatts (GW) to 64 GW), and cost between EUR 21-23 Bn by 2040 for the 60% scenario with a viable business case for only about 20% investments while 80% would have a negative payback at current commodity and technology prices. In the 80% scenario, the cost would rise to about EUR 55 Bn by 2050 and in the 95% scenario, the cost would be as high as EUR 71 Bn until 2050. Implementation of a different selection of options could increase CAPEX further. The main factor dictating the relative contributions of the six different options is the pricing of electricity (base and peak pricing), especially with regards to the business case.

The 60% scenario implies energy demand (including feedstock) be reduced by 12% while direct CO2 emissions be reduced by 46%. The scenario also implies industrial indirect CO_2 emissions to increase by 11 Mt CO_2 by 2040 unless an 80% renewable energy supply is available. The 80% scenario implies industry energy demand (including feedstock) reduced by 17% and industrial direct CO_2 emissions reduced by 74%. The 80% and 95% scenarios will have implications like a shift from fossil-based electricity generation to renewables (from 16 Mt CO_2-eq to 0-6 Mt CO_2-eq), electrification of industry amidst growing electricity demand (up to 560 PJ in 2040 including an additional 6 GW renewable energy and other sources such H_2), and future electricity price.

The main factors determining the relative contributions from each option on each scenario were the future price of energy (most influential factor), commodity prices, equipment costs and the extent to which industrial companies pursue other priorities. Under each scenario, the key parameters taken into account were: CO_2 emissions (direct and indirect) per industrial sector, energy source per sector and correlated CO_2 emissions, regional mapping clusters of emissions and energy demand. The roadmap scenarios clearly distinguish between efficiency improvements, system developments and technological innovations. Demand side measures focus strongly on circular economy (reuse, remanufacturing and recycling) influenced by the 'Nederland circulair in 2050'. Two of the six decarbonisation measures directly involve circularity: 'Develop routes to reuse and recycle materials' (mitigation potential of 1 Mt CO_2) and 'Develop CCS/U' (mitigation potential of 3 Mt CO_2).

The roadmap lists three key policy recommendations: develop a master plan for decarbonisation, optimise planning for long-term economic value, and structure public incentives to support the master plan.

- Steel Roadmap (Sweden) (2018)

The roadmap, drawn by the Swedeish steel industry, aims for a fossil-free and competitive Swedeish steel sector in line with Sweden's ambition to become one of the world's first fossil-free welfare countries. The Swedish steel industry has a vision that assumes that the steel industry will remain in Sweden by 2050 and that the steel industry is at the forefront of technology development, has employees who can develop new social solutions and create environmental benefits with their products. The climate roadmap is a step on the road to the vision.

The roadmap's technology portfolio includes: 1) the development of a brand-new process technique which uses hydrogen to reduce iron ore to iron (which at the current level of production means an increased need of about 15 TWh electricity), 2) the development of bio coke for reduction of iron ore for powder production and for scrap melting processes (requires a suitable source of carbon, processes for coke production and access to biomass for bio coke at a cost equal to that of fossil coke which at the current level of production requires at least 1-1.5 TWh), 3) the use of bio-based gas as a substitute for the fossil fuels used in heating and heat-treatment processes where electrification is not an alternative (which requires access to a gas of the same quality as natural gas and liquefied petroleum gas and competitive related to international energy costs. The estimated need is at least 2-3 TWh at the current level of production). These measures however demand extensive, long-term research efforts including testing at pilot- and demonstration levels.

It makes the following policy recommendations: 1) ensure a solid base for global competitiveness through efficient transportation and infrastructure, secure power supply, top class competence supply and appropriate operating conditions such as harmonised taxes and duties, 2) ensure financing for long-term research and knowledge development, also ensuring that the government campaign Industriklivet (Industrial stride) is maintained over parliamentary terms, 3) provide secured access to electricity and bio-based energy at internationally competitive costs, 4) facilitate increased collection of steel scrap and support the development of refined sorting of scrap, 5) invest more and faster in climate-smart means of transport such as railways and, as the steel industry recommends, development of more electric highways and 74 tonne trucks, 6) assure efficient and predictable permit processes, including required time plans and adaption of legal frameworks to European legislation, and 7) contribute to a larger visibility by supporting further development of qualified life cycle based models for declaration of climate impact.

The roadmap also registers industry pledges to continue: 1) to help its customers to create climate-smart and resource-effective solutions with Swedish steel so that their production, use and recycling become as efficient as possible, 2) to actively focus on research within prioritised areas which result in reduced direct emissions of fossil carbon dioxide, 3) to evaluate its value chains to reduce the total emissions through active choices of transport, raw material and more efficient recycling, 4) to implement new techniques for reduced emissions when commercially competitive, 5) to f urther develop analysis and reporting models and declare relevant data so that the customers can evaluate the environmental performance of their suppliers´ products.

- Arcelor Mittal (2019)

The roadmap focuses on the EU steel industry with a 2050 perspective and 2015 baseline and develops three net-0 pathways: Clean Power, Circular Carbon, Fossil Fuels with CCS. In the Clean Power pathway, the main focus is on Iron Electrolysis (tbd) and Green Hydrogen DRI which have a CAPEX + OPEX between +60-90%. In the Circular Carbon pathway, the main focus is on Smart Carbon (BFBOF+CCS) which have a CAPEX + OPEX between +20-35%. In the Fossil Fuels with CCS pathway, the main focus is on Blue H2 DRI (CAPEX + OPEX between +30-55%), DRI-EAF+CCS (CAPEX + OPEX between +35-55%), and BFBOF + CCS (CAPEX + OPEX between +30-50%). The technology portfolio includes: Torero: reducing iron ore with waste carbon, IGAR: reforming carbon to reduce iron ore, Carbalyst: capturing carbon gas and recycling into chemicals, Carbon2Value: capturing fossil fuel carbon for storage or reuse, H2 Hamburg: reducing iron ore with hydrogen, and Siderwin: reducing iron ore via electrolysis. It estimates the commercial horizon for these technologies at: Iron Electrolysis (20-30yrs), Green Hydrogen DRI (10-20 yrs), Smart Carbon (5-10 yrs), Blue H2 DRI (10-20 yrs), DRI-EAF+CCS (5-10 yrs), BFBOF+CCS (5-10 yrs).

It stresses the following policy needs: green border adjustment, energy infrastructure and allocation by sector, update the benchmark methodology for free allocation in Phase 4 of the EU ETS to make it technically feasible, private and public investment support. It estimates policy scenarios to either Stagnate, Wait, Accelerate Regionally, or Accelerate Globally. Three key underlying principles of this roadmap are supporting the advancement of renewable energy, accelerating the circular economy, creating industrial symbiosis.

- Eurofer (2019)

The roadmap focuses on the EU steel industry and putsforward 7 decarbonisation scenarios for 2050 with 1990 as a baseline: Business as usual, Ongoing retrofit' pathway, Current projects' pathway with low-CO2 energy, Alternative pathways' with low-CO2 energy, Current projects' pathway with CO2-free energy, Alternative pathways' with CO2-free energy, and Stagnation Scenario - Current Projects Pathway. . In the Business as usual scenario, the sector decarbonises only 10% by 2050. This scenario assumes that no technological development takes places; no new processes come on stream; the production mix remains the same and projected demand is met using existing installed capacity. In the 'Ongoing retrofit' pathway, the sector decarbonises 15%, requiring 55Twh/yr Electricity, Overnight Investment of EUR 34 Bn, and CAPEX+OPEX - EUR 74-91/yr. The scenario includes an 'ongoing retrofit' of existing facilities, which keeps the current share of production technologies, namely Blast Furnaces/Basic Oxygen Furnaces and Scrap-Electric Arc Furnaces, constant until 2050. In the 'Current projects' pathway with low-CO2 energy, emissions reductions stand at 74% (or 221 Mt CO2) [or 67% without CCS] alongside electricity consumption of 162Twh/yr for steel production and 234 TwH/yr for H2 production. It estimates 5.5Mt/yr Hydrogen use and 21MtCO2/yr CO2 stored. It estimates overnight Investments at EUR 52 Bn and CAPEX+OPEX between EUR 81-112/yr.

In the 'Alternative pathways' with low-CO2 energy, the sector decarbonises 80% with electricity consumption of 132-165Twh/yr for steel production and 119-275 TwH/yr for H2 production. It estimates 2.8-6.4Mt/yr Hydrogen use and 63MtCO2/yr CO2 stored. Overnight Investment are valued at EUR 58 Bn with CAPEX+OPEX between EUR 86-117/yr. This pathway assumes a combination of Scrap-EAF and the lowest emission technology from CDA and SCU respectively. In 'Current projects' pathway with CO2-free energy, sector decarbonization stands at 86%, with electricity consumption at 162Twh/yr for steel production and 234 TwH/yr for H2 production. It estimates 5.5Mt/yr Hydrogen use; 21MtCO2/yr CO2 stored, overnight Investment of EUR 52 Bn, and CAPEX+OPEX of between EUR 81-112/yr. This scenario looks at the remaining emissions in the core stream and downstream emissions, requires CO2-free energy, green electricity and green gas applications displace natural gas. In the 'Alternative pathways' with CO2-free energy, the sector decarbonises 95%. Electricity consumption is around 132-165Twh/yr for steel production and 119-275 TwH/yr for H2 production. In this scenario, there is 2.8-6.4Mt/yr Hydrogen use and 63MtCO2/yr CO2 stored with overnight Investment of EUR 58 Bn and CAPEX+OPEX between EUR 86-117/yr. Alternative pathways used with green electricity and green gases. Finally, in the Stagnation Scenario - Current Projects Pathway, sectoral decarbonisation of 79% is foreseen. This scenario could result in emissions of 64 million tonnes of CO2 in 2050 and occur if EU imports of semi-finished and finished steel products were to further increase, displacing production of crude steel in the EU.

New Breakthrough Technologies include H2-DRI-EAF; IBRSR - CCS; ETGR - CCU; BFBOF - CCU; BFTGR/BOF - CCS. The roadmap makes a number of assumptions: 1) marginal production growth up to an annual production of 200 million tonnes of crude steel in 2050, which represents a growth rate of about 0.5% growth per year compared to 2010 production levels overlaid on a supposed technology mix for the 'current project' pathway, 2) were EU steel production to continues to stagnate, remaining at the 2015 level (166 million tonnes of crude steel), the emissions reduction level could in fact be higher than if production growth were to continue to rise until 2050, as estimated in this study, 3) the initial setup of the 'current projects' pathway assumes a power grid mix of 80g CO2/kwh in 2050, focuses on the core stream emissions, and hinges on the assumption of a 'closed loop' in 2050 for all CCU products, 4) a transformed, future EU steel sector will have substantial demand for energy estimated to be around 400 TWh/year, consisting both of low-carbon electricity purchased from the grid for steel production processes (about 162 TWh/year) and the production of about 5.5 million tonnes of green hydrogen (about 234 TWh/year), and 5) scrap availability increases at 0.5% per year upto 2050.

- Material Economics (2019)

The roadmap focuses on the EU steel industry with a 2050 perspective and 2015 baseline and develops three net-0 pathways: New Process Pathways, Circular Economy Pathway and Carbon Capture Pathway. In the New Process Pathway, electricity input to EU steel production increases 113% or 335TWh/yr while investment in production capacity of crude steel increases by 60%. In the Circular Economy Pathway, electricity input to EU steel production increases 72% or 200TWh/yr while investment in production capacity of crude steel increases 25%. In the Carbon Capture Pathway, electricity input to EU steel production increases 72% or 200TWh/yr while investment in production capacity of crude steel increases by 65%. Key technologies include: CCU, SR+CCS, H-DRI, Low-CO2 EAF. The roadmap makes two main assumptions: that steel production stabilises at around 190 Mt from the 2040s as the steel stock saturates at 13.7 tonne steel per capita, and that in a high recycling scenario, the scrap share of steel production would reach 70%. In a low-scrap scenario, scrap-based inputs would stay between 50% (today's level) and 60%. Depending on how demand develops, the EU would then export as much as 38-63 Mt of scrap per year by 2050.

Studies

- ESTEP (2017)

The study looks at the European steel industry's potential for decarbonization between 2018 and 2030. The paper offers a global vision on the innovation and R&D initiatives which will lead to the achievement of the objectives identified in the frame of a sustainable lead ership of the EU steel sector. It assesses that for low carbon steelmaking: initatives such as The Big Scale initiative, can contirubte to reduce GHGs on two pathways: (1) Carbon direct avoidance (CDA), which substitutes carbon as the reducing element with hydrogen or via the use of electricity, (2) Low carbon without CO2emissions LCWCE), which further optimises carbon-based metallurgy and applies CCS/CCU methods to mitigate GHGs. It deems it essential to introduce Life Cycle Thinking and the SOVAMAT initiative, which puts forward the concept of "social value". Digital technologies for environmental impact assessment e.g. Cyber-Physical Systems, Internet of Things (IoT) and Big-Data Technologies would also be important. Continued recycling is essential to keeping scrap in a constant loop. Cascading use of resources, waste recycling, internal residues recovery and recycle are actions that can contribute to circularity of steelmaking. Steelmaking also results in useful by-products, such as process gases and ferrous slag, which substitute natural resources in other sectors and contribute to resource efficiency. The report highlights 4 ULCOS breakthrough routes (ULCOS-BF, HISARNA, ULCORED and ULCOWIN/ULCOLYSIS) which combine many mitigation paths and are designed to reach very high CO2 mitigation in steel production (50 to 90%, the latter if CCS is available).

The technology portfolio includes life cycle thinking, life cycle assessment, Cyber-Physical Systems, Internet of Things (IoT) and Big-Data Technologies, Circular economy practices incl. industrial symbiosis, Eco-design and eco-labelling directives, Continued improvement of existing production routes e.g. recovery of waste heat, optimization of operation using control models and expert or guiding systems, Plant-wide Energy Management Systems, leaner use of raw materials: use of secondary iron (scrap), use of raw materials of lower quality, yield improvements, recycling of societal residues, limit use of critical raw materials, in the BF-BOF route: switch from carbon to alternative reducing agents such as green H2 or electricity, the use of pre-reduced material with CH4), better internal use oftheir energy-containing by-products (e.g. heat recovery from slags), CCS/CCU, integration of H2 production tech, and the developments under the Big Scale Initiative: industry 4.0, General concepts of I²M (vertical integration, horizontal integration, transversal integration.

- Wesseling et al., (2017)

This study focuses on all European energy intensive industries and positions them within the transitions literature by characterizing their sociotechnical and innovation systems in terms of industry structure, innovation strategies, networks, markets and governmental interventions. It explores how these characteristics may influence the transition to deep decarbonization and identify gaps in the literature from which an agenda for further transitions research on energy intensive industries is formulated and considers policy implications. It identifies 6 barriers to innovation in energy intensive industries: 1) long investment cycles provide few windows of opportunity for changing technology, 2) the low, cyclical profit margins in energy intensive industries reduce the availability of investment capital and increase the return on investment times, 3) the high costs and potential loss of market share due to failures in the production process increase the risk perception of innovation, 4) little opportunity for testing and upscaling of innovations, 5) the incremental improvements to core process technologies over the past decades, often century, disadvantage radical innovations, leading to lock-in, and 6) the focus on refurbishing existing large-scale plants (so-called brown field investment), particularly in industrialized countries, inhibits more radical innovation.

To understand the dynamics of the decarbonization transition in energy intensive industries, this study distinguishes between innovations that range from marginal to significant (described as low carbon innovation) GHG emission reductions. These innovations may reduce emissions purposefully or not (sometimes emissions reductions are only a co-benefit, for example of energy efficiency and recycling), as well as directly (e.g., emission capture) or indirectly (e.g., lower electricity demand). It studies the following technologies: all energy intensive industries (Energy efficiency, Material Efficiency & Recycling, CCS), Steel (Recirculating Blast Furnace & CCS, Smelt reduction & CCS, Direct reduction with H2, Electrowinning), Chemicals (Advanced steam crackers & CCS, Electro-plastics (with RESMethane; with Fischer Tropsch), Bio-based polymers) (other sectors overlooked in this summary).

It puts forth policy recommendations: 1) stronger market-pull policy that supports low carbon innovation to move beyond the demonstration stage, 2) public procurement to reward low carbon innovation, 3) subsidizing renewable energy to facilitate fuel switching, 4) stimulating voluntary efforts (e.g. LEGO´s search for a green plastic); 5) labelling to create carbon foot print transparency, 6) regulation (e.g. banning petroleum based plastic bags), 7) quota based systems and feed-in-tariffs for green materials and carbon pricing, 8) risk sharing by the government, 9) enable long term direction of technology development, stakeholder-oriented, low-carbon scenario, vision and pathway processes, and 10) a globally coordinated policy approach.

- Climate Strategies and DIW Berlin (2018)

This study focuses on the basic materials industry and puts forward a portfolio of seven major mitigation options. These include: Share, Repair and Reuse. More and Purer Recycling, Material Efficient Design of Products, Efficient Manufacturing, Material Substitution, Low-Carbon Processes, Reduce Plant Emissions. It highlights an array of policy instruments for unlocking these mitigation options – including existing and not-yet existing tools. These include: LCA Labels, Eco design, Standards, Disclosure in Financial Reporting, Environmental Management Systems, Advice, Training, Networks, Green Public Procurement, Waste Charge, Consumption Charge, Innovation Support, Current ETS, Cfd, Infrastructure. The study then discusses criteria for prioritizing policy instruments: first, prioritize instruments that support multiple mitigation option, second, prioritize instruments that align private choices with long-term policy objectives, third, prioritize instruments that are complementary, fourth, prioritize policy and experimentation in individual Member States.

- Wyns, T., Khandekar, G., Robson, I. (2018)

The study focuses on 11 energy intensive sectors - iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferro- alloys and silicon, pulp and paper, ceramics, lime, and glass – as their input to the European Commission’s Strategy for long-term EU greenhouse gas emissions reductions. With 2015 as a baseline, the report catalogues the emissions and energy profile of the 11 EII. It highlights the constructive and solutions-oriented role that the EIIs have been playing, determines a combination of possible key solutions that will help EIIs to significantly reduce their emissions, as well as stress the need to address the necessary conditions to ensure that Europe is at the forefront of the energy and industrial transformation.

The study provides an in-depth analysis of 9 key pathways applicable to most industries. These include: Further energy efficiency improvements and energy savings, Process integration, Further electrification of heat, Further electrification of processes, Use of low-CO2 hydrogen, Valorisation of CO2 (Carbon Capture and Utilisation), Use of biomass, Carbon Capture and Storage, and Higher valorisation of waste streams and materials efficiency. It identifies six main categories of key framework conditions: R&D challenges, Securing adequate and competitively priced low-CO2 electricity supply, Infrastructure needs, Financing challenges, Conditions for enhanced circularity and materials efficiency, and Regulatory challenges. It then provides a 9-point regulatory framework to ensure that EIIs successfully transition to a low-CO2 economy while maintaining basic materials production, which is essential to all and in particular green value chains, in Europe:1) Protection against unfair international competition towards a level playing field, 2) Full carbon leakage protection from both direct and indirect costs of the EU ETS, 3) A large and ambitious mission oriented RD&I program for industrial low-CO2 technologies, including funding for industrial demonstration and scale up, 4) Competitively priced, carbon-neutral energy, 5) Consistency within the energy and climate policy framework to ensure that energy consumption and low-carbon policies are compatible, 6) Reconsideration and a better alignment of the environmental state aid guidance, 7) Industrial symbiosis and a circular economy through the effective combination of energy recovery and recycling, 8) Streamlining of the permitting procedures allowing a timely and predictable set of infrastructures and interconnections, and 9) Transparent accounting framework for CCU across sectors and value-chains to allow business cases to emerge

- Lechtenböhmer, S., Schneider, C., Vogl, V., Pätz, C. (2018)

The REINVENT project report serves to study and understand low-carbon transitions in the steel sector and provide a systematic review of existing knowledge of decarbonisation potentials and capabilities. A value-chain perspective is taken on in order to relate the different innovations to each other to analyse their decarbonisation potential. This systemic approach encompasses both technical and non-technical potentials. The review highlights interrelations within the value chain as well as inter-sectoral links. This report provides an overview on the European steel sector, its historical trends and projections for the future. Thereafter, it brings an analysis of the steel sector as an innovation system, drawing on the concept of value chain capabilities. Options and methods for decarbonisation are discussed and classified in line with IPCC schemes. These include: EMISSION EFFICIENCY (Electrowinning, Hydrogen Direct Reduction, Carbon capture and storage or utilisation, Increased share of secondary steelmaking), MATERIAL EFFICIENCY (Material efficient production and design, Material substitution), PRODUCT-SERVICE EFFICIENCY, SERVICE DEMAND REDUCTION, and ENERGY EFFICIENCY.

The report also assesses current initiatives on energy efficiency and deep decarbonisation as well as successes in and barriers for innovation. It highlights market-ready and implemented innovations such as: Consteel, Mootral, MicroZinQ, S-in motion, BSB prefabricated high-rise construction, Rotary Hearth Furnace Dust Recycling System, Arcelor's waste tires in EAF, phs-directform, and phs-ultraform. It also presents recent innovations under research and development: Dri Hydrogen (Hybrit, Salcos, GrinHy, H2Futures, SuSteel), Electrowinning (Siderwin), CCU/S (Carbon2Chem, Hisarna, Steelanol, Stepwise, FreSme, Valorco, Carbon4Pur, i3upgrade) and Process optimization (IGAR). The report makes the following recommendations: 1) pursuing CCS can create new cross-sectoral interdependencies, but pose challenges in the long-term to reach decarbonisation targets; 2) the electrification options offer the potential for energy storage and large-scale balancing of variable power and could build upon existing scrap-based production sites, 3) other side effects for the sector could be the independence from coal imports and, or, the growth of new markets, for example for HBI and oxygen, 4) large expansions of renewables capacity as well as the related infrastructures will be needed to meet the additional power demand when converting the industry from coal to electricity, and 5) a strong innovation pathway towards a decarbonised European steel system.

- Carbon Market Watch (2015 and 2019)

Key recommendations of the 2015 report are to: • Deliver a more meaningful carbon price signal that rewards green innovators • Phase out the free allocation of pollution permits • Target free allowances only to those that really need it • Annually reduce the amount of free allowances that an installation receives (benchmark) in line with the overall decarbonisation pathway of the EU ETS • Invest more auctioning revenues in climate friendly innovation and support frontrunners that want to invest in breakthrough technologies • Assist local communities and workers in regions impacted most strongly by the ongoing transition to a decarbonised economy by setting up a Just Transition Fund.

Key recommendations of the 2019 report are to: • Develop a climate-proof industrial strategy for energy-intensive industries, that helps set Europe on the path to achieving net-zero carbon emissions by 2040 • Put forward an industrial climate policy framework that includes at least the following components: 1. A Paris Agreement compliance test for environmental permitting 2. Increased funding for industrial decarbonisation 3. Carbon performance standards for the production and consumption of energyintensive materials in Europe 4. Provisions to incentivise the use of products which contain increasing rates of recycled materials 5. A phase-out of free EU ETS allowances 6. Improved public procurement rules for energy-intensive materials and products.

- Climate Strategies (2019)

The study focuses on the decsrbonisation of the European energy intensive industry sector by 2050 and proposes the following policy recommendations: 1) A Climate Contribution as part of the EU Emissions Trading System as a charge on carbon-intensive materials sold for final use in Europe which could be a pragmatic alternative to the Border Tax Adjustments , 2) Project-based Carbon Contracts for Difference (CCFDS) which could create lead markets for innovative low-carbon production processes and materials at national and European scale, 3) Contracts for Difference for Renewables which would help hedge renewable energy investors against regulatory risks such as changes in the power market design and address market failures that limit the role of private long-term contracts for mitigating electricity price risks, 4) Green Public Procurement (GPP) which would allows local, regional and national authorities to use their spending power when buying infrastructure or buildings to create lead markets for low-carbon practices and design, and 5) Product Carbon Requirements that help effectively ban the sale in Europe of products comprising materials produced with carbon-intensive processes. The study estimates that these policies in combination would a) create markets for the industry to pursue transformative innovation and investments towards climate neutrality production and use of materials and b) Contribute to a just industrial transition by preventing relocation of production and jobs to other regions that may currently implement less stringent climate policies.

The study focuses on the following five technological mitigation options to advance the climate neutrality of basic materials: Share, repair and reuse, Material substitution, Low-carbon production processes, and More and purer recycling.

- Wyns, T., Khandekar, G., Axelson, M., Sartor, O., Neuhoff, K. (2019)

This report builds upon the growing momentum for an EU industrial transition to net-zero amongst policy makers and even industry, and sketches the blueprint of such an industrial strategy towards climate neutrality. The policy-side twin of the IT50 Material Economics-led research, this report identified policy options to address key challenges industry faces on the transition path to climate neutrality. It also indicates how this policy set can be integrated into an industrial strategy and what governance instruments could guide to a successful implementation. This report focuses on the European basic materials industries and related value chains, with a specific focus on the iron and steel, cement, and chemicals sectors.

This report considers six main challenges to a climate-neutral industry: 1) Innovation gaps from basic R&D towards the deployment of new technologies, 2) An insufficient circular and materials efficient economy, 3) Barriers to market entry for low-CO2 solutions, 4) Lack of streamlining between the energy and industrial transition to climate neutrality and infrastructure needs for the transition, 5) Possible bottlenecks in scaling up investments and the risk of high-carbon lock-ins and 6) The complexity of integrating different types of policy instruments, policy areas and competences into a cohesive (industrial) strategy.

The report then puts forth 6 overarching and nearly 70 specific instruments to address the transition challenges: Innovation framework for a climate neutral industry, An enhanced circular economy package for basic materials, Creating competitive lead markets for low-CO2 solutions, Aligning the energy and industry transition and enabling infrastructure for industrial transition, Scaling up investments and avoiding high-carbon lock-in, Designing an industrial strategy for climate neutrality.

12.1.4 Paper Sector

Roadmaps

- CEPI, 2011

The roadmap focuses on building a low-carbon European (EU 28) forest fibre industry and offers a pathway to achieve up to 80% decrease in sectoral CO2 emissions by 2050 (12 Mt CO2 for pulp and paper in 2050 with 1990 as a baseline – no data for wood products) whilst accounting for competitiveness and future consumer demand. The roadmap does not develop its own scenario but adopts the European Commission (EC) Roadmap's Global Action Scenario With Available Technologies and evaluates three technologies pathways (Best Available Technologies or BAT, Emerging Technologies or ET, and Breakthrough Technologies or BTT) to achieve the goal. However, in contradiction to the EC, the roadmap predicts emissions reductions up to 2050 to be non-linear rationalised by the assumption that CO2 reductions under ET will be gradual.

The roadmap estimates CO2 emission reductions by 2050 of 25% with the BAT pathway, 50% with the ET pathway under current investment patterns, and 80% with the BTT pathway (BTT commercially available by 2030 allowing 10 years of optimization). The BAT pathway implicates upgradation of equipment to more efficient and commercially available models by 2050. While CHP is recognised as a key BAT, CCS or new solutions are also highlighted as necessary. Assumptions include a continuing trend for more electricity-based and less heat-based production equipment. In the ET pathway, the pulp and paper industries focus on improving efficiency of existing processes. The pathway also looks at new products, such as for the production of nano-cellulose. Other ET like energy conversion, biomass and waste/residue gasification, torrefaction, carbonisation and pyrolysis are also considered. For wood products, the ET pathway promotes new laser cutting technologies, material savings, wood drying concepts and the development of glues, paints, coatings and further treatment for increasing the durability of wood. The BTT pathway provides solutions for improving resource efficiency, energy efficiency, conversion efficiency, and product efficiency. The roadmap envisages CCS as a BTT, albeit, with delayed application.

It is further recognised that emission reductions can be met through increased recycling and improved sorting through technology-based, social and policy measures. The roadmap underscores integration of new markets, new bio-based products, recycling concepts, waste, energy and the vital impact of consumer preference for the bio-economy. It also explores other non-technological energy saving solutions and value adding options: fuel mix change, production of transport fuels, development of improved species, new harvesting techniques, improved sustainable forest practices and production of forest residues. Industrial symbiosis can be found with the waste sector. CCS facilities moreover can render these sites carbon-free.

The roadmap does not use economic modelling but assents to the EC's Primes scenario with the exception of the EC's 20% rise in sectoral final energy demand and that imports of biomass or wood will not increase to meet demand for large-scale electricity production. Sectoral growth is expected to be in line with EU GDP of 1.5%/year until 2050, with 50% more added value by 2050. The roadmap's policy recommendations include: sector-specific industrial policy packages beyond carbon pricing, EU ETS auctioning revenues as an innovation finance tool, multi-stakeholder sector transformation partnerships, include sector specific innovation support systems in Horizon 2020, a dedicated recycled materials policy, policy support for a shift towards a bio-based economy and a sustainable biomass supply policy.

- CEPI, 2017

The roadmap addresses the forest fibre and paper industry's path to 80% GHG emission reductions relative to 1990 levels by 2050 (reducing carbon emissions from 60 Mt to 12 Mt of which 10 Mt direct emissions, 1 Mt transport emissions and 1 Mt emissions from purchased electricity). The roadmap models six actions through which 48 Mt of carbon reduction could be achieved by 2050. These are: Energy Efficiency Improvements, Demand-Side Flexibility, Fuel Switch, Emerging and Breakthrough Technologies, Carbon Reduction from Purchased Electricity and Transport Improvements. Energy efficiency improvements include a combination of process improvements, including transition to industry 4.0, as well as investment in state-of-the-art production technologies and can reduce 7 Mt CO2. Demand-side flexibility includes leveraging on-site cogeneration assets to engage on the energy market and adapt energy sourcing to profit from low prices, in particular, from surpluses of intermittent renewable energy. This action can reduce 2 Mt CO2. Fuel switch through further conversion of industrial installations to low-to no-carbon energy sources can reduce CO2 emissions by 8 Mt. Emerging and breakthrough technologies both under development and other innovative and disruptive solutions can reduce CO2 emissions by 5 Mt. As the European power sector decarbonizes, a carbon reduction of 11 Mt from purchased electricity (indirect emissions) can be achieved. Finally, improvements in transport through greater fuel and transport efficiency, improved infrastructures, inter-modality and use of alternative transport fuels, such as biogas, advanced biofuels, electricity or fuel cells' can reduce CO_2 emissions by 4 Mt.

The roadmap stresses the importance of commercial availability of ET and BTT (approximated abatement from BTT being 5 Mt CO_2). It estimates 40% more investment than 2010 levels would be needed, with an estimated EUR 24 Bn extra investment. A further investment of EUR20 billion would be needed for the production of new bio-based products. Projected costs refer to CAPEX only and not R&D expenditures. The roadmap does not employ any economic modelling but estimates the industry's value added compared to 2010 to increase by 50% (approximately EUR 25 Bn by 2050). It underscores a shift to the circular bio-economy by building on the assets of forest fibres such as renewability, carbon sequestration and recyclability. The potential for industrial symbiosis is identified with the waste sector.

The roadmap outlines policies needed to embed a pro-investment approach in four areas: reducing regulatory costs, addressing investment risk profiles, matching investment life cycles and preventing regulatory uncertainty. These require policy focus on: building a vibrant bio-economy (at the centre of the EU framework for R&I and other EU policies), European R&D focus on development and deployment of ET and identification of BTT, elimination os policy measures encouraging low-efficient energy and prioritising recycling, greater electricity market design to complete EU market integration and remove regulatory barriers to unleash the potential of industrial demand-side flexibility, cost and resource efficient reduction of transport emissions, development of skills and education, and facilitating access to finance particularly for SMEs.

Studies

- CEPI, 2013

The Two Team Project was set up by CEPI to identify BTT in the industry. 8 breakthough concepts presented and assessed. These include Deep Eutectic Solvents, Flash Condensing with Steam, Supercritical CO_2, 100% electricity, Steam in paper drying, DryPulp for cure-formed paper, Functional surface. The winning innovation was Deep Eutectic Solvents.

12.1.5 Food Sector

While an EU sectoral roadmap for the food and beverages industry has not been developed yet, there has been a study on 'a CO_2, waste and water neutral food industry by 2030 (2013) for Flanders. This study and its approach form a highly interesting template for a broader industrial low-carbon roadmap for Flanders. This comes from the fact that the food-sector roadmap not only tackles GHG emissions but also addresses waste and water resources in an integrated manner (including an assessment across food-sector related value chains). The food roadmap furthermore sets very specific ambition levels (e.g. KPI's) in each of these areas and has developed a toolbox of possible actions. While the roadmap shows a theoretical high potential for achieving ‘neutrality’ targets, it also highlights major barriers for practical implementation. The report further highlights possible conflicts between energy and raw materials demand (for instance, the energetic use of organic waste vis a vis their use as a circular resource in other sectors). Both, the highly interesting scientific approach and the integrated assessment across GHG emissions, waste (circular economy) and the energy system, make this roadmap’s approach a good example for replication in a broader industrial low-carbon framework for Flanders. Importantly, the know-how for the implementation of such an approach resides within Flemish research institutes and should hence be easily accessible.

13. References

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