Industrial Value Chain

A Bridge Towards a Carbon Neutral Europe

Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions

VUB IES INSTITUTE FOR EUROPEAN STUDIES

7 September 2018

THIS CONTRIBUTION WAS COMMISSIONED BY

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ABOUT THE IES

The Institute for European Studies (IES) at the Vrije Universiteit Brussel (VUB) is an academic Jean Monnet Centre of Excellence and a policy think tank that focuses on the European Union in an international setting. The Institute advances academic education and research in various disciplines, and provides services to policy-makers, scholars, stakeholders and the general public.

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European energy intensive industries (EIIs) quintessentially form the foundations of the European economy. As enabling materials industries, they link to every possible economic sector, including each other, forming an intricate arterial system of value chains. The energy intensive industrial sector in the European Union (EU) holds strategic importance given that around 80% of the goods produced by the EII are consumed all over Europe.

This report represents the joint contribution from 11 European Energy Intensive Industries (EIIs) - *iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferro- alloys and silicon, pulp and paper, ceramics, lime, and glass* - to the European Commission's Strategy for long-term EU greenhouse gas emissions reductions.

The goal of this contribution is to highlight the constructive and solutions-oriented role that the EIIs have been playing, determine 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.

PROFILING EUROPE'S ENERGY INTENSIVE INDUSTRIES

EMISSIONS

Energy intensive industries have played an important role in helping Europe meet its current climate ambitions. Between 1990 and 2015, EIIs reduced their greenhouse gas emissions by 36% and accounted for 28% of the total economy-wide emission reductions by the EU even though they represented 15% of EU total GHG emissions (excl. LULUCF) in 2015 (18.4% in 1990).

These reductions have come about due to a combination of factors:

- Improvements in energy efficiency
- Fuel switching including increased use of biomass
- Closures and lower production levels or capacity utilisation in some sectors, in particular following the economic crisis of 2008
- Deep reductions of non-CO_2 GHG emissions in chemicals and fertilizers production (N_2O and fluorinated gases emissions reduced by 93% between 1990 and 2015 in these sectors).

Not only have EIIs more than disproportionately helped reduce emissions from their own sectors, but also contribute to emissions reductions in other sectors like transport, buildings, waste and power generation. Today, Europe's energy intensive industries are at the forefront of low-carbon solutions.

ENERGY CONSUMPTION AND EVOLUTION

Between 1990 and 2016 EII final energy consumption dropped by almost 2 EJ (from 11.7 EJ) or 20%, while the share of EIIs in the EU's final energy consumption fell from 23% to 19%. Overall, energy intensity declined by 39% across all industrial sectors together. Over the period 1990-2016 the use of fossil fuels too reduced significantly.

RAW MATERIALS USE

Next to energy, raw materials (including feedstocks) form the main input for the EII. The most important raw materials for the EII are crude oil (refining), naphtha (from crude oil refining to petro-chemicals), natural gas and potash (fertilizers), iron ore (steel), limestone (cement and lime), clays (ceramics), wood (pulp and paper), sand (glass), and ores (non- ferrous metals and ferro-alloys). Some of the raw materials used by EII feature in the EU's list of critical raw metals 2017 e.g.phosphate rock (fertilizers), cobalt (steel), coking coal (steel) and a number of non-ferrous metals. Some EIIs remain highly dependent on raw material imports into the EU: the vast majority of ores used by the steel, non-ferrous metals and ferro-alloys and silicon sectors are imported. In other cases, the raw materials are quite abundant and locally sourced. Recycled materials form, next to virgin raw materials, a high share of the inputs.

ECONOMIC PROFILE

EIIs were seriously affected by the economic crisis and the after-effects are still visible as scar-tissues. Between 2000 and 2016, output fell in all sectors (except the chemicals sector and pulp and paper industry) while in some EII like steel, cement, refining, pulp and paper, glass, ceramics, and lime, large industrial closures ensued. To date, with the exception of only the chemical sector, no other EII has achieved pre-crisis level production. While GVA amongst the EII as a whole grew 19% (2000-2016), the rest of the EU economy grew faster.

VALUE CHAINS AND LOW-CARBON VALUE CHAINS

Energy intensive industries are of strategic importance to current European value chains, critical to each other's value chains and at the forefront of low-carbon solutions. The flow of materials to and from the EIIs forms a highly dense, integrated network with each other and every other sector (rest of the economy). EIIs in fact enable the European economy. Looking ahead EIIs are vital to enable a carbon neutral Europe: some of the most iconic examples of low-carbon solutions like electric vehicles, wind turbines, solar PVs or battery storage are enabled by EIIs.

SOLUTIONS SPACE

EIIs have embraced the need to transition to a low-carbon economy and have played a constructive role by developing solutions for their sectors while also assisting other parts of the economy through their products, symbiosis, services to energy, and enabling higher levels of circularity and waste valorisation. The Solutions Space details the solutions emanating from the EIIs themselves.

OVERVIEW OF TECHNOLOGY SOLUTIONS TO REDUCE EIIS GREENHOUSE GAS FOOTPRINT

A detailed technology assessment of more than 80 low-CO_2 technology options (multiple options per industrial sector) has been conducted across all energy intensive industries. The assessment can be found as addendum to this document. A selection of main pathways applicable to most industries is presented in-depth in the text. These include:

- Further energy efficiency improvements and energy savings
- Process integration
- Further electrification of heat
- Further electrification of processes
- Use of low-CO_2 hydrogen
- Valorisation of CO_2 (Carbon Capture and Utilisation)
- Use of biomass
- Carbon Capture and Storage
- Higher valorisation of waste streams and materials efficiency

The table below gives a basic overview of the potential to apply the main technology pathways mentioned above at sectoral level. The goal is to visualise pathways that apply across multiple sectors, but this does not imply that the actual pathways will follow this assessment (e.g. due to further R&D barriers and other framework conditions not materialising). The mitigation potential of the technologies presented is not always cumulative and in some cases one technological pathways might exclude another.

	Electrification (heat and mechanical)	**Electrification (processes: electrolysis/ Electrochemistry excl. H2)**	**Hydrogen (heat and/or process)**	**CCU**	**Biomass (heat and feedstock)/ biofuels**	**CCS**	**Other (including process integration)**
Steel	**xxx**	xx	xxx	xxx	x	xxx	Avoidance of intermediate process steps and recycling of process gases: xxx Recycling high quality steel: xxx
Chemicals fertilizers	xxx	xxx	xxx	xxx	xxx	xxx(*)	Use of waste streams (chemical recycling): xxx
Cement Lime	xx (cement) x (lime)	o (cement) o (lime)	x (cement) x (lime)	xxx (cement and lime)	**xxx** (cement) x (lime)	xxx (cement and lime)	Alternative binders (cement): xxx Efficient use of cement in concrete by improving concrete mix design: xxx Use of waste streams (cement): **xxx**
Refining	xx	o	xxx	xxx	xxx	xxx	Efficiency: **xxx**
Ceramics	xxx	o	xx	x	x	o	Efficiency: **xxx**
Paper	xx	o	o	o	**xxx**	o	Efficiency: **xxx**
Glass	xxx	o	x	o	xxx	o	Higher glass recycling: xx
Non-ferrous metals/alloys	**xxx**	**xxx**	x	x	xxx	x	Efficiency: **xxx** Recycling high quality non-ferrous: xxx Inert anodes: xxx

o: Limited or no significant application foreseen
x: Possible application but not main route or wide scale application
xx: medium potential
xxx: high potential
***xxx**: Sector already applies technology on large scale (can be expanded in some cases)*
(*) in particular for ammonia and ethylene oxide

Table i: Overview of low-CO_2 technology potential for energy intensive sectors

The next table presents an assessment across these main pathways identified in terms of technology status, impact on energy use, CAPEX (relative to investments in current state of the art), OPEX (relative to current operations), infrastructure needs and possible co-benefits.

	Technology status	Energy use - compared to current operations	CAPEX – relative to conventional technologies	OPEX – compared to current operations	Infrastructure needs	Possible co-benefits
Electrification heat	High TRL except for high T furnaces (glass, cement)	Higher electricity demand but primary energy use can be lower	Depends (replacement of boilers relative low additional CAPEX, (high T) furnaces major investment)	Depends on (favourable) electricity vis-à-vis natural gas prices and efficiency improvements from electrification.	medium	Higher potential for electricity demand response. Possible energy savings.
Electrification processes	In most cases not reached demonstration stage	Higher electricity demand but primary energy use can be lower	High	Highly dependent on electricity prices	Low/medium (might be need for more/ upgraded HV connections)	Higher potential for electricity demand response
Process integration	Move towards pilot and demonstration plants	Medium/high	Medium (unless combined with CCU or CCS)	higher	Medium (unless combined with CCU or CCS)	Recycling/ process internal use of generated process gases
Hydrogen	Mov towards pilot and demonstration plants	High electricity consumption for electrolysis based production	High	Higher (dependent on electricity prices)	High (unless H_2 production happens on site)	Possibility of power storage (e.g. use of ammonia as carrier)
Biomass	Diverse, move towards pilot and demonstration plants for newest technologies	Can be notably higher	High for feedstock applications (new process technologies) Low/medium for fuel applications (compared to e.g. natural gas based furnaces)	Higher for feedstock applications Comparable to conventional for some fuel applications (depends on price of biomass)	Medium/high (need for new and reliable logistics chains for sustainable biomass from within and imported into the EU)	Industrial symbiosis (e.g. use of biomass waste streams)
CCU	Moving towards commercialisation for carbonation and synthetic fuels. Other processes see move towards pilot and demonstration plants.	Can be very high for H_2 based routes. Limited for carbonation and mineralisation.	High (but lower for some carbonation technologies)	Can be High (esp. when H_2 from electrolysis is required. depends on renewable electricity price). Limited for carbonation/ mine ralisation.	High	CO_2 becomes resource instead of cost
CCS	Move towards pilot and demonstration plants	Will be higher	High	Higher	High	Possible process integration benefits

Table ii: Assessment of main technology options vis-à-vis technology status, energy use, CAPEX, OPEX and infrastructure needs

INDUSTRIAL SYMBIOSIS AND SYNERGIES WITH NON-INDUSTRIAL SECTORS

The value chain analysis reveals that basic materials industries have a strong connection with each other. The technology assessment indicates that industrial symbiosis will become more prominent as sectors seek to reduce greenhouse gas emissions. The refining sector and petrochemical industry are even physically integrated through large process installations (e.g. naphtha crackers). Primary steel productions deliver one of the most important constituents (i.e. granulated blast furnace slag) for the cement industry. Silica fume, which is a by-product of silicon and ferro-silicon, is added to concrete in construction, which contributes to a reduction of cement use while providing better performances. Lime forms an essential raw material for steel, paper and glass production and has played a vital role in reducing damaging emissions of sulphur dioxide. Cement and fertilizers contribute to recycle and recover waste and by products from other energy intensive industries. Industrial symbiosis is also already used extensively at site level with multiple production installations (e.g. exothermal processes delivering heat to processes requiring additional energy). There are examples of energy intensive industries delivering waste heat to other industries or sectors of the economy (e.g. paper production to automotive or waste heat used for district heating).

CIRCULAR ECONOMY AND MATERIALS EFFICIENCY

Most EII's have already incorporated circularity and materials efficiency in their business models to a large degree (e.g. through industrial symbiosis). For most basic materials, enhanced circularity will become more important over the next decades as a strategy to reduce emissions, reduce energy use, maintain security of supply (in some cases), and enhance production and growth while reducing costs.

There are factors which can help achieve higher levels of circularity in all the EII sectors, like the reduction of losses in the production of semi-finished and finished products, the prevention of down-cycling to lower-quality materials (in particular as concerns certain non- ferrous metals, ferro-alloys and plastics), the reduction of contamination of end of life materials streams, the development of new and more efficient separation technologies (for instance, to remove copper from steel which would allow up to 90% recycling of steel), and reduced recycling in mixed streams which results in higher losses. There are two vast yet mostly underused waste streams which can be exploited to achieve exponential levels of circularity: e-waste and construction and demolition waste.

While there is scope for (much) higher levels of circularity in relation to products by the EIIs, there exist important regulatory barriers in achieving higher levels of circularity and materials efficiency.

SYNERGIES BETWEEN THE EU'S ENERGY TRANSITION AND THE EIIS' LOW-CO_2 TRANSITION

From the list of low-CO_2 technology solutions mentioned before it follows that future demand for electricity can rise significantly if higher levels of electrification, use of hydrogen, valorisation of CO_2 and capturing of CO_2 are deployed across the energy intensive industries. To be consistent with the economy-wide carbon neutrality objective, this electricity will have to be generated without emitting CO_2 emissions. This additional demand will increase the challenge of greening current power demand progressively, which will already exert its requirements on replacing existing generation and providing solutions for increased renewables content which is bringing more and more variability in supply.

The EIIs can assist in enabling the EU's energy transition. Ideally a virtuous cycle is established between the transition of the EIIs and the overall energy transition of the EU. The main goal should be access to competitively priced, abundant and reliable low-CO_2 electricity on the one hand and identification of new or enhanced roles the EIIs can play in facilitating the energy transition on the other hand.

EMERGING BUSINESS MODELS

The transition to a low-carbon society, a circular economy and higher levels of digitisation will, under the right conditions, enable new business models or structures. These new business models or structures can potentially further strengthen existing value chains by filling in existing business gaps (see examples below), deeper integration with customer value chains, creating new, dynamic links leading to entirely new value chains, and fostering innovation and employment generation.

Innovation is intrinsic to new business models. New (unique) value propositions emerge through innovation but also as a way to increase economic resilience. In the industrial sector, nine types of business models have been identified. These are *industrial symbiosis* (e.g. valorisation of waste heat and materials waste streams), *Product Management Service*, *Cradle to Cradle* (C2C), *Green Supply Chain Management* (GSCM), *Circular Supplies business model, Product Life Extension, Lean manufacturing, Closed loop production*, and *Take Back Management* (TBM).

These new and emerging business models, hold the potential to generate higher levels employment. However, skills development will be a particularly important challenge.

FRAMEWORK CONDITIONS

While an exhaustive list of solutions towards further greenhouse gas emission reductions by EIIs has been identified, there are existential framework conditions that will need to materialise and barriers to be overcome before this potential can be realised.
Six main categories of key framework conditions were identified:

- R&D challenges
- Securing adequate and competitively priced low-CO_2 electricity supply
- Infrastructure needs
- Financing challenges
- Conditions for enhanced circularity and materials efficiency, and
- Regulatory challenges.

There are also two main horizontal constraints that impact all other framework conditions. The first horizontal constraint is that the industrial transition will have to happen in a highly competitive and dynamic international environment. Without ensuring a healthy industrial base in Europe there will be little scope for the development and deployment of low-CO_2 technologies in the EU.

The second horizontal constraint is time (and timing). For most energy intensive companies 2050 is just one (large) investment cycle away from today. This implies that the six framework conditions will have to be continuously and progressively addressed within 10 years at the latest to enable low-CO_2 technology investments in the right timeframe.

R&D CHALLENGES

A mission oriented R&D programme for energy intensive industries' low-CO_2 technologies will be a must. Three main challenges will have to be addressed.

First, most of the technologies assessed in this contribution hover at technology readiness levels (TRLs) between 5-7, with a large number of other technologies still awaiting to reach TRL 5. Designing and building a pilot or demonstration plant at scale forms indeed one of the biggest challenges for most of the low-CO_2 options on the horizon.

Secondly, while some supporting technologies are advancing well on their own, the integration of these into a full production system remains a challenge. Examples are the production of hydrogen, the transformation of biomass to fuels and technologies to capture CO_2 that will require integration into e.g. ammonia, steel, high value added chemicals and complete CCU and CCS systems.

Finally, even if the low-CO_2 technologies reach maturity, their market uptake will depend on the operational costs. This will have to become one of the main areas of further R&D. Cost optimisation can be achieved by having multiple technologies reach full scale size to allow for experimentations with design improvements on an industrial scale.

SECURING SUFFICIENT, RELIABLE AND COMPETITIVELY PRICED LOW-CO_2 ELECTRICITY

It is clear that higher levels of electrification in EIIs and new low-CO_2 processes (e.g. processes based on H_2 from water electrolysis, some CCU, recycling technologies, and CCS) will require significant amounts of electricity to operate. An indicative estimate based on sector studies and calculations gives a range of 2980 TWh to 4430 TWh aggregated possible future electricity demand from energy intensive industries following the wide-scale deployment of low-CO_2 processes.

It is however by no means certain that sufficient, reliable and competitively (and non- volatile) priced low-CO_2 electricity will be available to enable this transition. This will therefore be one of the most important framework conditions for the transition to a low- CO_2 industry in Europe.

The fact that industry will likely become the largest electricity consumer under 2050 scenarios together with the stringent requirements on price and adequacy will make the fulfilment of final electricity demand with renewable energy by 2050 much more strategic beyond planning for total final demand in the EU by 2050. Europe's energy and industrial transition cannot be seen in silos.

Current policies might stand in the way of higher electrification (including use of hydrogen) in EIIs. The indirect costs under the EU ETS are or can become a serious deterrent towards investments in (new) processes that require high amounts of electricity. Further efforts must be made to lower regulatory costs related to electricity consumption by EIIs on a level playing field basis across the EU and also vis-à-vis international competitors. Allowing EIIs across the board to sign long-term electricity contracts e.g. through renewable Power Purchase Agreements (PPAs) will help address risks related to price volatility and help reduce the cost of capital for utility scale renewables projects in the EU. Finally, there is also a risk that the development and deployment of low-CO_2 technologies in energy intensive industries, which can lead to increased energy use, will conflict with provisions in the EU's energy efficiency directive.

INFRASTRUCTURE NEEDS

There is an urgent need to strategically map the infrastructure needs in relation to an industrial low-carbon transition. A bottom up approach to identify these needs could be the way forward. Secondly, mapping should take into account existing connections between industrial clusters across borders (e.g. existing pipeline infrastructure connection regions) and how economic or other synergies between regions can be realised. Finally, the risk of industrial clusters becoming isolated from new low-CO_2 infrastructure must be identified together with options to mitigate this. This mapping exercise will give better insights into the capital needed for low-CO_2 infrastructure but also indicate priority areas and (need for) interconnections.

A new EU platform consisting of industrial actors, research and technology organisations (RTOs), technology and infrastructure providers should be established to map necessary future EU (cross-border) infrastructure for energy intensive industries. This platform shall by 2025 propose a first list of European industrial projects of common interest related to infrastructure for further development and financing. No single company or sector will be able to provide the capital for these infrastructure investments on their own, hence instruments will have to be developed to assist with enabling the financing.

CAPEX AND OPEX CHALLENGES IN AN INTERNATIONAL COMPETITIVE ENVIRONMENT

Industrial roadmaps and pathways developed in recent years at sectoral and/or national levels give some insights into the CAPEX and OPEX needs for industrial low-CO_2 transformation. However, there is currently there is no estimate of aggregate additional CAPEX needs across EIIs in the EU towards 2050 reduction pathways. It seems clear however that the CAPEX required for an industrial low-CO_2 transition in the EU will, in all sectors mentioned, be well above their current investment levels in the EU.

The strategic relationship between OPEX and CAPEX in the context of a low-CO_2 transition is quite straightforward. High CAPEX investments in new processes with a significant higher OPEX compared to (international) competitors will likely not happen. There is no business case to be made. Therefore (as stated before) future EU R&D missions will have to focus on enabling low-CO_2 technologies to deliver OPEX that is competitive with conventional production technologies. Furthermore, energy carriers that will become the main vectors for low-CO_2 processes (e.g. electricity and hydrogen) need to remain competitively priced in Europe for energy intensive industries. In particular, regulatory costs are of concern here. Finally, it will take time for new processes to iron out (first of a kind) issues that hamper process efficiency, leading to (much) higher costs initially. It is therefore important the EU supports the creation of lead markets through public procurement, which will allow innovative producers and processes gain access to the market. This approach will also apply to new product types (or even business models) with a much lower CO_2 footprint for which there is currently no market. Another instrument that can help with market creation (or prevent loss of market share) is the smart use of standardisation.

Finally, for most energy intensive industries, the current production location has significant strategic value (e.g. connections to infrastructure and logistics, proximity to raw materials supply chains and/or customers). Most investments in low-CO_2 processes will therefore likely happen at the same location. While retrofits of existing process installations towards low-CO_2 processes will likely be prioritised, this will however not always be possible. This implies that major brownfield conversions will have to be part of an industrial low-CO_2 transition. This type of transition will always be more expensive compared to greenfield developments. Existing productive assets will have to be dismantled and sites will have to be prepared for installation of new process facilities. This will pose major economic accounting issues for companies and can make the business case of low-CO_2 projects nonviable (even with attractive financing programmes). EU and national financing instruments will therefore need to take into account the additional constraints that come into play during the conversion of existing process installations which have been written off. This can include allowing for accelerated depreciation of the new assets (to lower taxation basis) which are being developed, other tax abatements and financial support for preparation of site conversion.

CONDITIONS FOR ENHANCED CIRCULARITY AND MATERIALS EFFICIENCY

All EIIs are extremely reliant on raw materials and almost all energy intensive industries already depend highly on recycled materials as raw materials input. Security of raw materials supply (especially critical raw materials) is indispensable for some sectors which rely heavily on raw material imports into the EU like the steel, non-ferrous metals, ferro- alloys and silicon, chemicals and fertilizers sectors. For most basic materials therefore, enhanced circularity will become even more critical over the next decades as a strategy to reduce emissions, reduce energy use, maintain supply security, and enhance production and growth while reducing costs.

In 2018, the EU adopted an ambitious waste framework directive with binding targets for recycling (55% by 2025 and 65% by 2035 for municipal waste, 65% by 2025 and 70% by 2035 for packaging waste). Mechanisms like Extended Producer Responsibility (EPR) which extends producer responsibility for a product beyond their scope have been pioneered in Europe nearly two decades ago. But there is still a need for more elaborate, ambitious European circular economy regulations with long term trajectories given that around 80% of the goods produced by the EII are traded all over Europe. While Europe is already a success story when it comes to steel, non-ferrous, paper or glass recycling for instance, important challenges remain in other value chains and in particular with regard to maintaining the quality of basic materials in recycled product streams.

These challenges and opportunities include support for EIIs that seek to collaborate and extract opportunities for symbiosis which will in turn preserve and strengthen European value chains. But also the need to ensure a level playing field for the use of biomass waste by removing subsidies that favour one industry over another. Furthermore, access to raw materials and enhanced waste recycling and the use of by-products should be facilitated and more efforts are needed to improve the sorting and recovery of valuable materials from waste streams whose recyclability potential is still untapped and where a higher quality of recovered waste can be achieved. Finally, a structured waste policy should recognise and reward the benefits of an effective combination of energy recovery and recycling where this combination is justified by life-cycle thinking on the overall impacts of the generation, management and fate of specific waste streams.

REGULATORY BARRIERS AND OPPORTUNITIES

Throughout this contribution, a number of regulatory barriers and opportunities has been identified which will determine whether EIIs will thrive and invest in the low-carbon transition.

Together these barriers and opportunities form nine key elements that would establish a supportive and stable regulatory framework needed to ensure that EIIs successfully transition to a low-CO_2 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-CO_2 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

9/ Transparent accounting framework for CCU across sectors and value-chains to allow business cases to emerge

THE WAY FORWARD – A NEW INDUSTRIAL STRATEGY

The existing framework for energy intensive industries to move ahead with enabling a low- carbon transition in Europe is unfortunately not adequate at this moment. The R&D gap towards demonstration and commercialisation of low-CO_2 technologies is not fully addressed and there remain major challenges to bring down CAPEX and OPEX of new technologies. Infrastructure that could enable the roll out of new processes across Europe is barely present and the financing instruments at EU and Member State levels to facilitate investments are insufficient. Furthermore, existing regulations can have a counterproductive effect. For instance, high and rising electricity prices as a consequence of EU and national regulations could close off the road to higher levels of electrification in energy intensive industries. Finally, the continued importance of maintaining a competitive industrial base is not well aligned across all policy areas, leading to an important risk of investment leakage (including of low-CO_2 investments).

The challenge of further significant greenhouse gas emission reductions in EIIs, especially given its urgency and scale and with regard to the long investment cycles of EIIs, is substantial. Therefore, ***a new and integrated EU industrial strategy for EIIs as part of a competitive low-CO_2 transition is needed***. This must include:

- The design and implementation of an EU flagship 'mission oriented' R&D programme that addresses the main challenges towards competitive low-CO_2 processes in energy intensive industries. Adequate support for demonstration of advanced low- CO_2 technologies towards market readiness.
- The strategic alignment of the EU's energy and industry transitions in particular with regard to adequate and competitive supply of low-CO_2 electricity to energy intensive industries.
- Development of adequate financing mechanisms to face the high CAPEX that comes with low-CO_2 process investments including support for replacement of existing and productive assets with low-CO_2 processes. A state aid regime that acknowledges the size and scope of the industrial low-CO_2 transition.
- Urgent strategic industrial low-CO_2 infrastructure planning with focus on regional and transnational industry clusters and industrial symbiosis and development of EU industrial projects of common interests.
- Smart regulatory instruments can assist with lead market creation for low-CO_2 products and processes. This includes the use of public procurement and development of low-CO_2 standards for products.
- Finally, during the transition continued protection for energy intensive industries should be provided to safeguard competitiveness and investments in Europe.

An EU Strategy for long-term EU greenhouse gas emission reductions will only be successful if it fully embeds such industrial strategy.

2. INTRODUCTION

2.1. PURPOSE OF REPORT

This document represents the joint contribution from 11 Energy Intensive Industries[1] (EIIs) in Europe to the European Commission's Strategy for long-term EU greenhouse gas emissions reductions. The goal of this report is to identify common challenges and constraints faced by European EIIs in meeting ambitious climate targets, determine a combination of key solutions that will help EIIs to significantly reduce their emissions, as well as address the necessary conditions for ensuring that Europe is at the forefront of the energy and industrial transformation.

The joint input to the Commission strategy is not a vision or a single "low-carbon" roadmap for the EIIs but a delineation of possible solutions and of the required framework conditions that are needed for European EIIs in order to enable a successful low-carbon transition.

2.2. SCOPE

This contribution focuses on the following EII sectors: iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferro-alloys and silicon, pulp and paper, ceramics, lime, and glass.

2.3. METHODOLOGY

The contribution starts by presenting a coordinated profile of the EIIs (chapter 3). This profiling is conducted through an assessment of the EIIs' greenhouse gas (GHG) emissions, energy consumption, raw materials use, economic profiling and value chains. It then highlights the essential role of the EIIs in the low-carbon economy in their quality of enablers of the economy.

Next, a 'solution space' is presented (chapter 4) which identifies, in detail, sector specific and collaborative solutions from the EIIs. This section demonstrates that EIIs have already been very active in researching and developing technological solutions towards lower CO_2 emissions and looks at other key areas in which EIIs can play an enabling role. The solution space section explores the likely application of ten different technological pathways across the different energy intensive sectors *(further energy efficiency improvements and energy savings; process integration; electrification of heat and processes; use of low-CO_2 hydrogen; carbon capture and utilisation and valorisation of CO_2; use of biomass; carbon capture and storage; enhanced valorisation of waste and materials efficiency and other promising technologies)*, the status of the pathways and how they could impact energy use, CAPEX, OPEX, infrastructure needs and possible co-benefits provided the appropriate techno-economic environment is in place.

1 CEFIC, the European Chemical Industry Council, CEMBUREAU, the European Cement Association, CEPI, the Confederation of European Paper Industries, CERAME-UNIE, the Liaison Office of the European Ceramic Industry, EULA, the European Lime Association, EUROALLIAGES, the Association of European ferro-alloy producers, EUROFER, the European Confederation of Iron and Steel Industries, EUROMETAUX, the European non-ferrous metals Association, Fertilizers Europe, the major fertilizer manufacturers in Europe, FuelsEurope, the European Petroleum Refiners Association, and Glass Alliance Europe, the European Alliance of Glass Industries.

It next delves into the prospects of industrial symbiosis and synergies with non-industrial sectors, the circular economy and materials efficiency, looks into the synergies between the EU's energy transition and the EIIs' low-CO_2 transition and explores the prospects of emerging business models that lead to higher value added but which reduce the materials and greenhouse gas emissions and energy intensity.

The contribution next presents a set of framework conditions or challenges (chapter 5) emerging from the solutions space. It identifies the key enabling conditions towards the solutions identified in chapter 4 and which existing or new barriers need to be overcome along six categories: R&D challenges, securing competitive low-CO_2 electricity, infrastructure needs, financing challenges, circular economy and materials efficiency challenges and regulatory challenges.

The conclusions of this report (chapter 6) bring together the solution space with the framework conditions and outlines possible ways forward. These could be used to develop a new EU industrial strategy for EIIs and their value chains towards enabling a carbon neutral EU.

The report is based on diverse sources and includes data from the EII as well as publicly available documents and data (e.g. industry reports, EU databases, European Commission studies, project websites and media articles). While every effort has been made to use strict sectoral delineations, where data was unavailable, corresponding NACE codes have been used (for instance: non-metallic minerals, base metals and so on). For the chemicals sector, pharmaceuticals have not been included, unless otherwise mentioned.

KEY MESSAGES

PROFILING ENERGY INTENSIVE INDUSTRIES

- EIIs are the lifeblood of key value chains in EU but also their supply chains are linked to other EIIs.
- EIIs products are and will be needed more to enable the energy transition and will be at the forefront of low-carbon solutions.
- EIIs reduced greenhouse gas emissions by 36% between 1990 and 2015 and contributed significantly to the EU's overall emission reductions in same period (-24% in 2015 ref. 1990).
- Final energy use was reduced by 20% between 1990 and 2016. A major fuel shift occurred away from solid fuels towards biomass, waste and electricity in same period. Most sectors showed significant efficiency improvements over this period.
- EIIs production was seriously affected through the economic crisis. Only chemicals production was above pre-crisis levels in 2017. Most EIIs have a high trade intensity and are exposed to a high-level of international competition.
- Most EIIs already see recycled materials, waste and by-products of other industries as important raw material inputs.

3. PROFILING EUROPE'S ENERGY INTENSIVE INDUSTRIES

3.1. THE VALUE OF EUROPE'S ENERGY INTENSIVE INDUSTRIES

As enabling materials industries, EII's form the backbone of the European economy. The flow of materials to and from the EIIs forms a highly dense, integrated network with each other and every other sector of the economy. EIIs are therefore of strategic importance to current European value chains, critical to each other's value chains and at the forefront of low-carbon solutions for Europe.

3.2. GHG EMISSIONS AND EVOLUTION

The total direct GHG emissions from EIIs, covered in this contribution, in the EU were 665 Mt CO_2-eq in 2015, representing 15% of EU total GHG emissions (excl. LULUCF) in 2015. Between 1990 and 2015 energy intensive industries reduced direct emissions by 36% (-375 Mt). They contributed 28% to the total economy wide emission reductions by the EU (-1331 Mt) over same period[2].

Direct CO_2-eq emissions	1990	2005	2015	% change 1990-2015	Absolute change (Mt) 1990-2015
Chemicals[3]	325.1	212	128.4	-61%	-196.7
Fertilizers4 [ammonia+nitric acid] (included in chemicals)	*76*	*66*	*28*	*-63%*	*-48*
Steel[5]	258	232	190	-26%	-68
Cement[6]	163	157	105	-36%	-58
Refining[7, 8]	122	143	137	+12%	+15
Pulp and paper[9]	39.9	43.2	32.7	-18%	-7.2
Ceramics[10]	26	26	17	-35%	-9
Non-ferrous metals and ferro-alloys[11]	52.3	31	17.8	-66%	-34.5
Lime[12]	25.9	23	19.4	-25%	-6.5
Glass[13]	*28*	*20*	*18.1*	*-35%*	*-9.9*
Total	**1,040**	**887**	**665**	**-36%**	**-375**
EU28 (excl. LULUCF)[14]	**5,650**	**5,220**	**4,319**	**-24%**	**-1,331**

Table 1: Evolution of greenhouse gas emissions (1990, 2005 and 2015) across energy intensive sectors and the EU as a whole

2 EU wide GHG reductions between 1990 and 2015 were -1331 Mt or -24%
3 Cefic *(Sector Data)*
4 Fertilizers Europe *(Sector Data)*
5 Eurofer *(Sector Data)*
6 WBCSD – CSI, 2018
7 FuelsEurope *(Sector Data – Concawe)*
8 For oil refining emissions went up between 1990 and 2015 because the energy requirement for the refining industry has increased due to two main reasons:
1) Improved quality of the fuels (more strengthen specifications).
2) Adaptation of the scheme to a changing demand, requiring deeper conversion of heavy products into light products. As a result of that, CO_2 emissions increased despite the energy efficiency improvement (15% improvement between 1992 and 2014) and fuel switching measures (natural gas / electricity) taken by the refining industry.
9 Cepi *(Sector Data)*
10 Cerameunie *(Sector Data)*
11 European Environment Agency, 2018a
12 EULA *(Sector Data)* and European Environment Agency, 2018b
13 Glass Alliance Europe *(Sector Data - 2005 and 2015)*; 1990 number extrapolated by IES-VUB using historical GHG efficiency improvements (1990-2015) and 1991 glass production index (Eurostat).
14 European Environment Agency, 2018b, p. ix

Almost all energy intensive sectors saw a significant reduction of GHG emissions between 1990 and 2015. This is due to a combination of factors:

- Improvements in energy efficiency (see section 3.3)
- Fuel switching including increased use of biomass (see section 3.3)
- Closures and lower production levels or capacity utilisation in some sectors, in particular following the economic crisis in 2008. (see section 3.5)
- Deep reductions of non-CO_2 GHG emissions in chemicals and fertilizers production (N_2O and fluorinated gases emissions reduced by 93% between 1990 and 2015 in these sectors).

EIIs have not only more than disproportionately helped reduce emissions from their own sectors, but also contribute to emissions reductions in other sectors like transport (excluding shipping and aviation), buildings, waste and power generation who accounted for 20.6%, 14.7%, 3.21% and (approx.) 20% respectively of total EU emissions in 2015[15]. The importance of the energy intensive industries to reducing emissions in other sectors of the economy is further developed in section 3.6.

3.3. ENERGY CONSUMPTION AND EVOLUTION

Table 2: Final energy use 1990, 2016 (EJ)[16]

Final energy consumption[17]	**1990 (EJ)**	**2016 (EJ)**	**% change 1990-2016**
Chemical industry (energetic use)[18]	2.9	2.2	-26%
Iron and steel[19]	3.5	2.0	-41%
Non-ferrous metals[20]	0.5	0.4	-21%
Non-metallic minerals[21]	1.8	1.4	-23%
Cement (part of non-metallic minerals[22]	*0.8*	*0.5*	*-37%*
Glass (part of non-metallic minerals[23]	*0.29 (2005 figure)*	*0.27 (2015 figure)*	*-6% (between 2005-2015)*
Lime (part of non-metallic minerals)[24]	*0.086 (2010 figure)*	*0.076 (2015 figure)*	*-12% (between 2010-2015)*
pulp, paper and print[25]	1.1	1.4	+25%
Refining[26]	1.8	1.9	+10%
Total	**11.7**	**9.4**	**-20%**

15 European Environment Agency in Council of the European Union, 2018 and Sandbag, 2016.
16 There is a discrepancy between the energy data form Eurostat and the data collected by sectors. This can relate to a difference in scope (e.g. exclusion of auto-generation of electricity) and classification and due to issues related to incomplete data-sets.
17 Excluding auto-generation of electricity (e.g. CHP and use of blast furnace gas for power generation). For refining, energy data from 'consumption of the energy branch' was used from the EU energy balances.
18 Eurostat, 2018a | For refining the energy data from section 'consumption of the energy branch' was used.
19 Ibid.
20 Ibid.
21 Ibid. The estimated shares of final energy consumption in 2012 for the subsectors in the non-metallic minerals sector (not identified in the Eurostat energy balance) are 17% for glass and glass products, 19% for ceramics and ceramic products, 58% for manufacturing of cement and 6% for production of lime. Source: ICF International, 2015
22 WBCSD-CSI 2018
23 Glass alliance Europe *(Sector Data)*
24 EULA *(Sector Data)*
25 Eurostat, 2018a
26 Ibid. | For refining, energy data from 'consumption of the energy branch' was used from the Eurostat, 2018a

Total final energy consumption of EIIs[27] in 2016 was 9.4 Exajoules (EJ). Between 1990 and 2016 final energy consumption dropped by almost 2 EJ (from 11.7 EJ) or 20%, while the total EU final energy consumption[28] went up by 1%. Between 1990 and 2016 the share of EIIs in the EU's final energy consumption fell from 23% to 19%.

The reduction of final energy consumption happened across most sectors over the period 1990-2016. Most noticeable reductions happened in iron and steel production (-41%), cement production (-37%)[29] and chemicals (-26%). In oil refining, energy use went up (+10%) between 1990 and 2016 due to increased energy requirement for the refining industry related to improved quality of the fuels and adaptation to a changing demand, requiring deeper conversion of heavy products into light products.

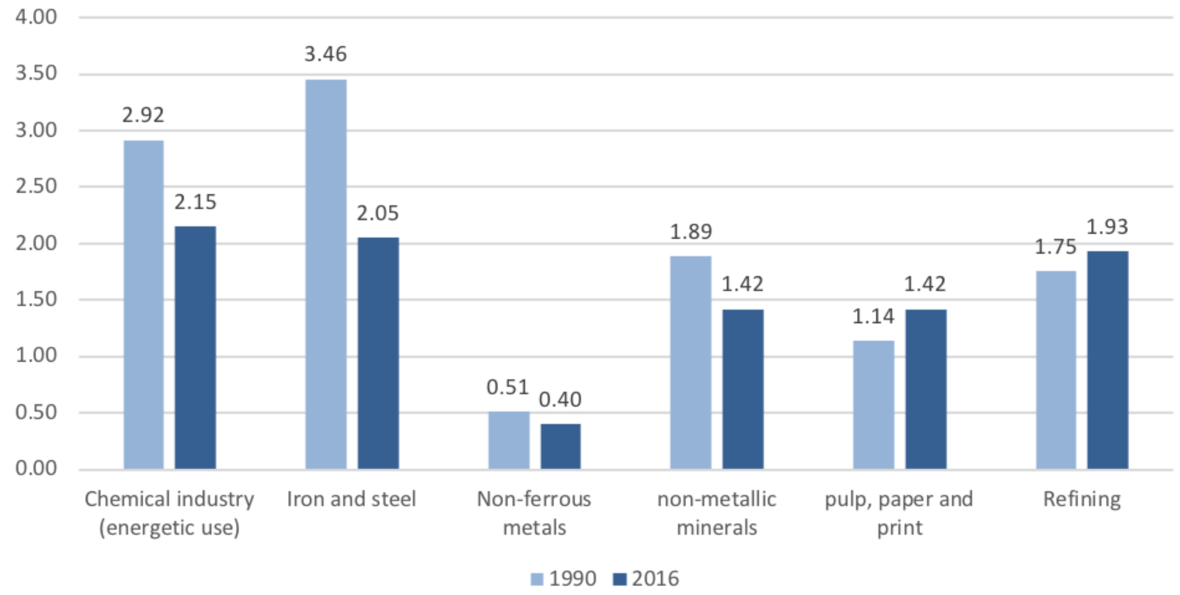

Figure 1: Final energy consumption[30] per sector and total across energy intensive industries (EJ, 1990 and 2016). Source: Eurostat, EU energy balances (2018 edition).

Most importantly, the energy intensity in the EIIs decreased over the past decades. Over the period 1990-2015, energy intensity declined by 39% across all industrial sectors together[31]. The chemicals industry[32] reduced its energy intensity by 60%. Between 2004 and 2011 the efficiency of ammonia production deteriorated slightly, but European ammonia production is already very efficient[33].

27 Excluding auto-generation of electricity (e.g. CHP and use of blast furnace gas for power generation). For refining, energy data from 'consumption of the energy branch' was used from the EU energy balances.
28 Eurostat, 2018a | For refining the energy data from section 'consumption of the energy branch' was used.
29 Ibid. The estimated shares of final energy consumption in 2012 for the subsectors in the non-metallic minerals sector (not identified in the Eurostat energy balance) are 17% for glass and glass products, 19% for ceramics and ceramic products, 58% for manufacturing of cement and 6% for production of lime. Source: ICF International, 2015.
30 WBCSD-CSI 2018
30 Glass alliance Europe (Sector Data)
31 EULA (Sector Data)
32 Eurostat, 2018a
33 Ibid. | For refining, energy data from 'consumption of the energy branch' was used from the Eurostat, 2018a. monia plants are, however, 20% more efficient with a specific energy usage of 28 GJ/t NH3. This is already close to the theoretical minimal energy consumption of 23 GJ/t NH3.

Between 1992 and 2014 refining industry energy efficiency improved by almost 15%[34]. Iron and steel production saw a 33% reduction in the energy used to produce a tonne of steel between 1990 and 2016. The latter change (but also part of the overall reduction of energy consumption) is due to the higher share of steel production in electric arc furnaces (from 30% of total EU steel production in 1990 to 40% in 2016)[35]. The production of cement in the EU saw energy intensity reduce by 9% between 1990 and 2016[36], due to energy efficiency investments and a reduced use of clinker in cement production. The aggregated non-metallic minerals sector saw an efficiency improvement of 13% and in the non-ferrous metals sector copper, nickel and zinc reduced energy intensity by 60%, 48% and 33% respectively between 1990 and 2014[37]. Finally, in the pulp, paper and printing sector, there was an efficiency improvement of almost 18% between 1991 and 2016[38].

Further improvements to energy efficiency in EIIs are likely subject to decreasing returns and will hence be harder to achieve. For example, in the chemical industry, the period between 2005 to 2015 shows less significant performance in energy efficiency compared to the decade before. Furthermore, some production plants in the EU are close to the thermodynamic limits of current processes. The thermochemical efficiency of current blast furnaces in the steel sector for example, is almost optimal. Similarly, current non-ferrous metals, ferro-alloys & silicon, glass, cement and lime plants are already operating very close to maximum efficiency with the future margin for efficiency improvements relatively small[39]. Section 4.3.2 will further discuss future technological and economic potential of further efficiency improvements in energy intensive industries.

Over the period 1990-2016, the use of fossil fuels reduced significantly. Solid fossil fuel use dropped by 49% while use of renewable fuels[40] (e.g. solid biomass, biogas, biofuels and municipal waste) increased by 123%. The use of industrial and (non-renewable) municipal waste also increased dramatically (+331%), in particular as a fuel in the production of cement. The drop in solid fossil fuel use happened across all industries: refining (-96% between 1990 and 2016) iron and steel production (-40%), chemicals production (-61%), non-ferrous metals (-81%), non-metallic minerals (-65%) and pulp and paper (-61%).

The fuel shift is also visible in the relative share of energy carriers which moved away from solid fuels (from 23% of final energy consumption in 1990 to 14% in 2016) and shifted towards higher use of renewable fuels (from almost 3% in 1990 to 7% in 2016) and electricity (19% to 22%). Oil products' share dropped slighted (24% to 22%) and the share of gas remained stable at 28%.

34 FuelsEurope *(Sector Data - Solomon Associates)* | taking into account complexity of different refineries and additional energy requirements following environmental protection measures (e.g. desulfuring).
35 Eurofer *(Sector Data)*
36 WBCSD-CSI, 2018. | Combination of thermal energy use (excluding drying of raw materials) and on electricity consumption.
37 Eurometaux, 2016, p.2
38 CEPI, 2018a, p. 27 | From 15.78 TJ/kt in 1991 to 12.98 TJ/kt in 2016
39 In the non-ferrous metals sector, incremental improvements continue to be made through continuous technology upgrades. For example, in the aluminum sector, incremental technology for primary production is making progress through one of the recent p ilot projects located in Karmoy, Norway. Still in its pilot stage, this is the ultimate technology to reduce electric ity consumption with carbon anodes, with a potential of 15% electricity consumption compared to today's global figures.
40 The following sources are included in renewable fuels (for the sectors considered here): Solar thermal, Solid biomass, charco al, biogas, municipal wastes (renewable), bio gasoline, biodiesel, other liquid biofuels and geo-thermal.

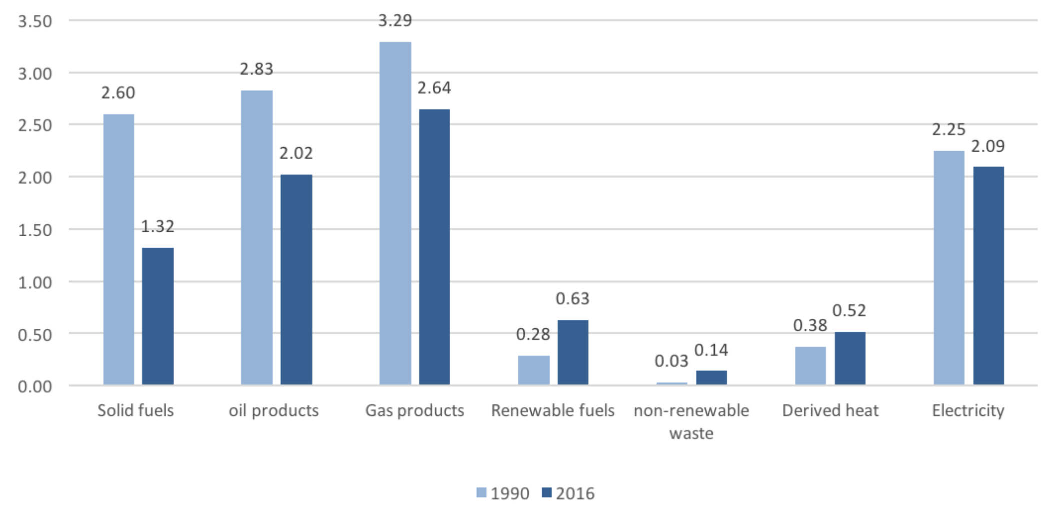

Figure 2: Final energy consumption[41] per energy vector in energy intensive industries (EJ, 1990 and 2016)
Source: Eurostat, EU energy balances (2018 edition)

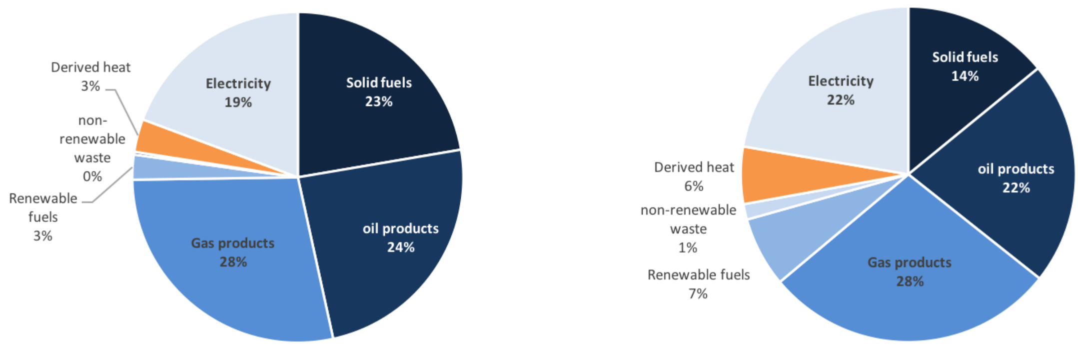

Figure 3: Fuel shift in final energy consumption of energy intensive industries % of total consumption, 1990 (left) and 2016 (right)
Source: Eurostat, EU energy balances (2018 edition)

3.4. RAW MATERIALS USE

Next to energy, raw materials (including feedstocks) form the main input for the EII. The most important raw materials for the EII are crude oil (refining), naphtha (from crude oil refining to petro-chemicals), natural gas and potash (fertilizers), iron ore (steel), limestone (cement and lime), clays (ceramics), wood (pulp and paper), sand (glass), and ores (non- ferrous metals and ferro-alloys). Some of the raw materials used by EII feature in the EU's list of critical raw metals 2017 e.g. phosphate rock (fertilizers), cobalt (steel), coking coal (steel) and a number of non-ferrous metals[42]. In other cases, the raw materials are quite abundant and locally sourced[43].

41 Eurostat, 2018a | For refining, energy data from 'consumption of the energy branch' was used.
42 A large number of critical raw materials are non-ferrous metals. Non-ferrous metals critical raw materials include: Antimony, Beryllium, Cobalt, Gallium, Germanium, Indium, Silicon metal, Tantalum, Tungsten, Vanadium. Several of these critical raw materials are produced as by-products of base non-ferrous metals.
43 Access to land and lengthy permitting procedures can be an obstacle to raw materials availability.

Sector	Raw Materials
Chemicals	Naphtha, LPG, Gas Oil, Ethane, Metals, Minerals, Sugar, Starch, Fats *Recycled Plastic and other materials*
Fertilizers	Natural Gas, Potash, **Phosphate Rock** *By-products from other industrial sectors*
Steel	Coal, Iron Ore, Anthracite, Limestone, Dolomite, Olivine, Pulverised Coal, Pellets, External Scrap, Lime **Cobalt, Coking Coal, Fluorspar, Magnesium, Niobium, Tungsten, Vanadium** *Scrap steel*
Cement	Gypsum, Limestone, Pozzolana, sand, clays **Bauxite** *Blast Furnace Slag, Fly Ash*
Refining	Crude Oil, Natural Gas (Including LNG), biomass
Pulp and Paper	Wood, Non-Fibrous Materials, Lime *Paper Waste*
Lime	Limestone
Glass	Sand, Sodium Carbonate, Limestone, Dolomite *Recycled Glass*
Ceramics	Clay, Kaolin, Sand, Feldspar, Silicate , Minerals, Magnesite, **Bauxite**, Dolomite, Wollastonite
Non-ferrous Metals	Non-ferrous metal Ores (incl. **bauxite**), Wastes **Antimony, Beryllium, Cobalt, Gallium, Germanium, Indium, Silicon metal, Tantalum, Tungsten, Vanadium** (several of these critical raw materials are produced as by-products of base non-ferrous metals) *Recycled Non-Ferrous Metals*

Table 3: Raw materials and feedstock used by energy intensive industries
(critical raw materials in bold, recycled materials in italics)

Figure 4 shows the most important feedstocks for cokes production (used in steel production) and petrochemicals. In 2016 the total feedstock (non-energetic) use for petrochemicals in the EU was 3.17 EJ - a 9% increase compared to 1990 (2.91 EJ) [44]. Demand and imports for LPG in particular has grown consistently over the years. Crude oil inputs for refining were 24.37 EJ in 2016 (almost 0.5 EJ or 2% less compared to 1990)[45]. The apparent consumption[46] of other important raw materials for energy intensive industries is shown in figure 5.

44 CEFIC, 2018 | Feedstock can make up as much as 60% of the production cost in the European chemical industry (however, the chemicals sector enjoys access to key raw materials (e.g. for oil and naphtha) at zero or low import duties.

45 Eurostat, 2018a

46 Apparent Consumption = Production – Exports + Imports

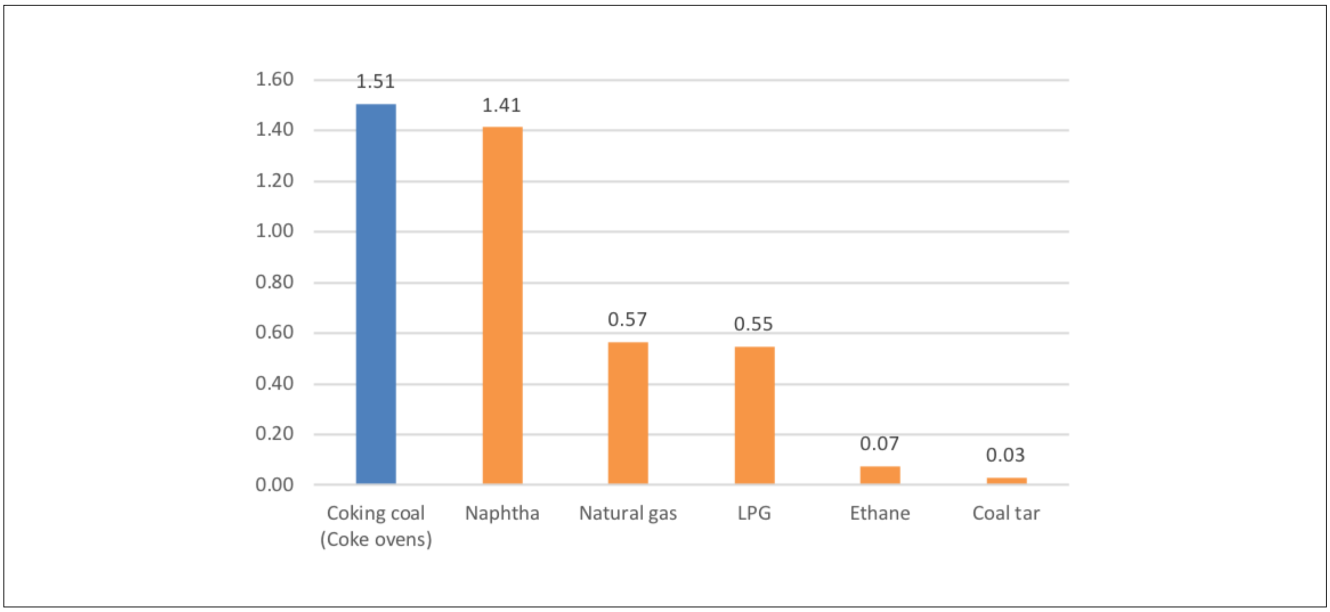

Figure 4: Feedstock 2016 in EJ (blue: cokes ovens, Orange: petrochemicals)
(Source: Eurostat EU energy balances - 2018 edition)

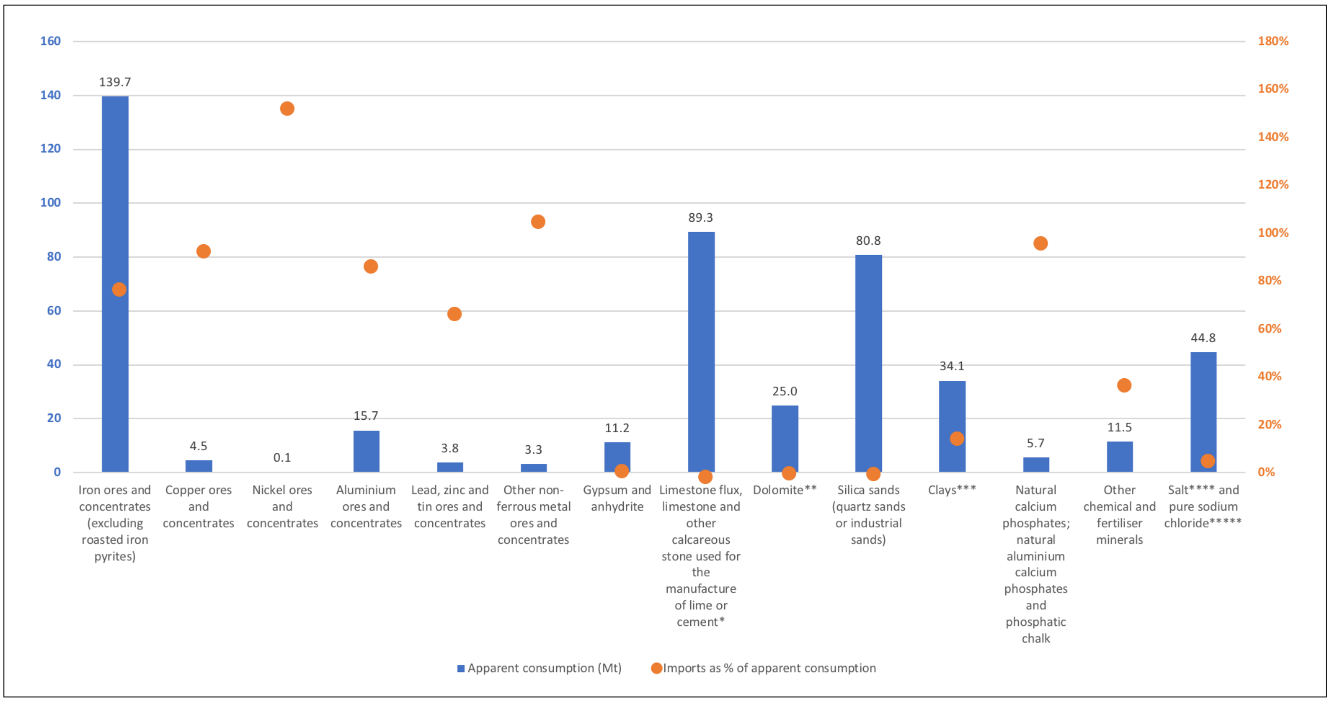

Figure 5: Raw Materials Apparent Consumption 2017 in Mt (Economy-wide statistics)
(Source: Eurostat)

Some EII are less reliant on supply security than others. For the cement and lime sectors, limestone is abundantly available and locally[47] sourced. Moreover, the cement industry already replaces some of its raw natural resources with waste and by-products from other industrial processes[48].

47 Land-use planning practices and permitting procedures across Europe can be described as a complex interaction between local, regional, national and European levels. Lack of common policies and complicated mining and/or environmental permitting proced ures are limiting the access to materials since many years (less permits, short duration of permits, expensive, time-consuming procedures for both operator and authorities). By improving the policy and regulatory framework conditions of the extractive industries, the Euro pean Union will foster the supply security of raw materials within Europe.

48 CEMBUREAU *(Sector Data)* | In recent years, about 3-4% of raw materials used in the production of clinker in Europe consisted of alternative raw materials and ashes from fuel, totalling about 14.5 million tonnes per year.

About 82% of raw material for the pulp and paper sector is sourced in Europe.[49] Main Glass sector raw materials originate from the EU[50] while some critical raw material (e.g. rare earths) are used by the sector only in niche production and very low tonnages. However, other EII remain critically dependent on raw material imports into the EU. In the case of fertilizers, the share of imported finished nitrogen (N) fertilizers in total EU consumption has been 23-30% while the EU produces only 0.3 Mt of Potash fertilizers as compared to the total EU consumption of 2.6-2.7 Mt[51] . The vast majority of ores used by the steel, non-ferrous metals and ferro-alloys and silicon sectors are imported. Crude oil is manly imported from outside the EU and Norway, but the wide diversification of supply sources reduces the criticality of import dependence.

Next to virgin raw material use, recycled materials form a high share of the inputs. In 2017 the use of scrap steel in crude steel production stood at 55.6% (scrap inputs represented 94 out of 169 Mt of crude steel production in the EU). In 2016/2017 90% of non-ferrous metals were recycled from buildings, 90% from transport and 60% from packaging. In 2016, 27.1 million tonnes of plastics post-consumer waste was recovered of which 5,3 million tonnes was used for recycling in Europe. This yielded about 3.7 million tonnes of plastic recyclates used to produce products (assuming a 70% recycling yield). The total converter demand for plastics was 49.9 million tonnes, hence recycled plastics represented about 7.4 % of the converter demand in Europe in 2016[52]. In 2017, 56.8 Mt of paper waste was collected in the EU of which 48.3 Mt (85%) was used for recycling. In paper production, 54% of fibrous input materials consisted of recycled paper and 46% of wood derived pulp. Out of the total mass of paper consumed in the EU in 2017, 62% was recycled paper (i.e. 48.3 Mt out of 77.8 Mt total consumption)[53]. In 2014, the EU consumption of container glass was 19.7 Mt and 14.6 Mt was collected for recycling, representing a 74% recycling rate. In the production of container glass (around 21 MtCO_2), 11 Mt cullet was used, representing 54% of materials input[54]. The fertilizers sector uses 5.1 Mt of ammonium sulphate generated from nylon production, 5.2 Mt of sulphur generated as a by-product from refineries and sulphuric acid from non-ferrous metals production[55].

3.5. ECONOMIC PROFILE

Total aggregate production value for EIIs in 2015 was nearly EUR 1.3 trillion[56] (see figure 6 for sectoral figures) while the gross value added (GVA) was EUR 378 billion[57] in the same year. Between 2000 and 2016, output fell in all sectors (except the chemical sector which saw growth of 13%[58] and pulp and paper industry with pulp production almost at the same levels in 2016 compared to 2000 and paper and paper board 3% higher[59]). Only the chemical sector has achieved pre-crisis level production. In some of the EII's like steel, cement, refining, pulp and paper, glass, ceramics, and lime, large industrial closures happened between 2000 and 2016 and in particular during the crisis time (see figures 7 and 8).

49 CEPI *(Sector Data)*
50 FEVE, 2015; p.13 | For instance, a recent study by the container glass industry (FEVE – 2015) showed that, on average, more than 70% of raw materials used in container glass production travel less than 300 km prior to being incorporated into a glass furnace
51 Fertilizers Europe *(Sector Data)*
52 PlasticsEurope and additinional information by CEFIC (Sector Data)
53 CEPI statistics 2017 (2018)
54 FEVE 2018
55 Fertilizers Europe, 2017
56 Eurostat, 2018b; 2013 figure was used for manufacture of refractory products.
57 Eurostat 2018c
58 Eurostat 2018d
59 CEPI, 2018a and 2018b

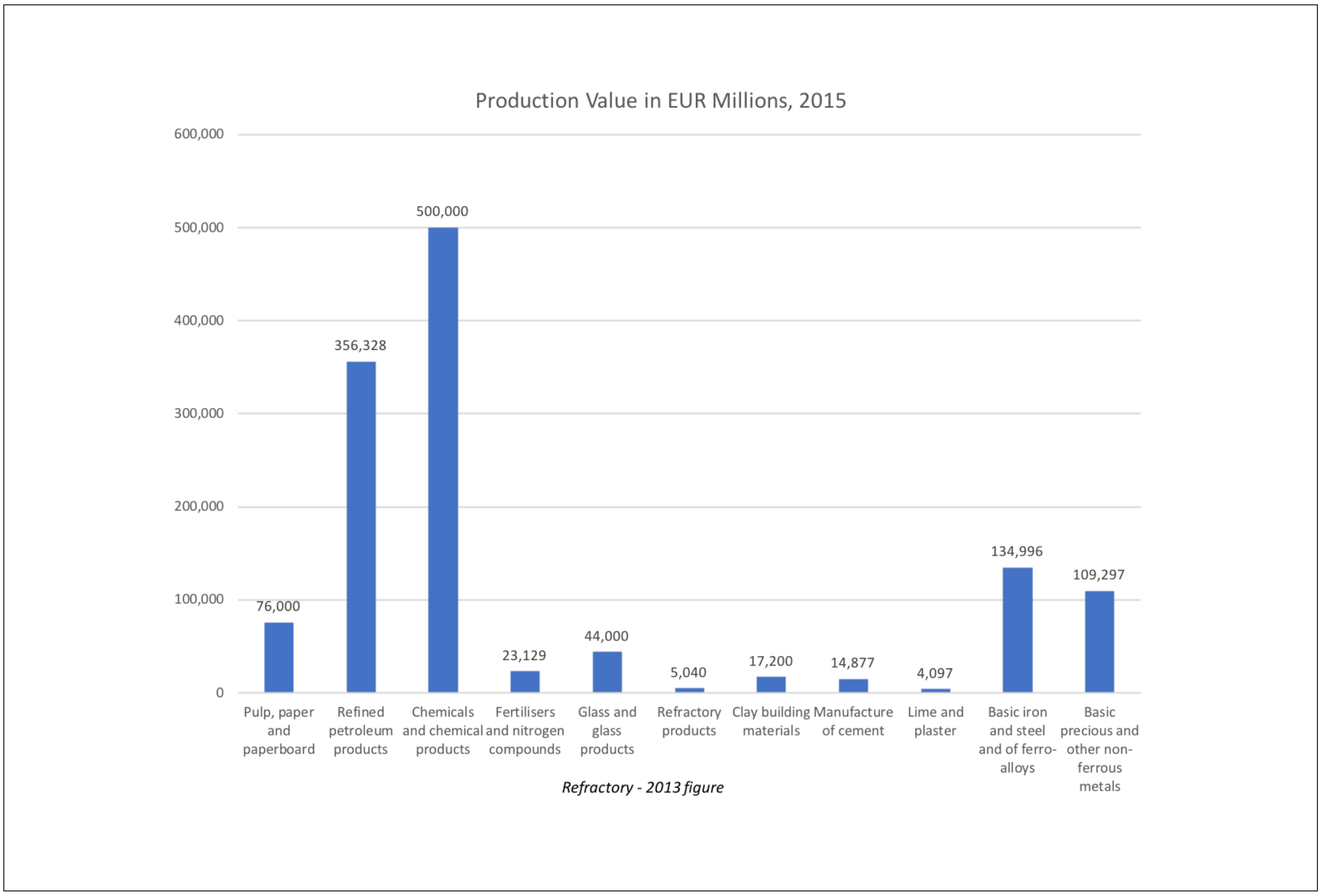

Figure 6: Production value (million EUR), 2015 for energy intensive industries
(Source: Eurostat)

While production hasn't recovered in most EII, GVA shows a different picture. GVA amongst the EII (sum of GVA of paper and paper products, refining and coke, chemicals and chemical products, non-metallic minerals and basic metals)[60] as a whole grew 19% from EUR 320 Bn in 2000 to EUR 381 Bn in 2016. Nonetheless, the rest of the EU economy grew faster (in GVA terms), compared to the aggregate of sectors presented (see figure 9). Since 2000, the GVA of the EU economy as a whole grew 54%.

60 Eurostat, 2018c

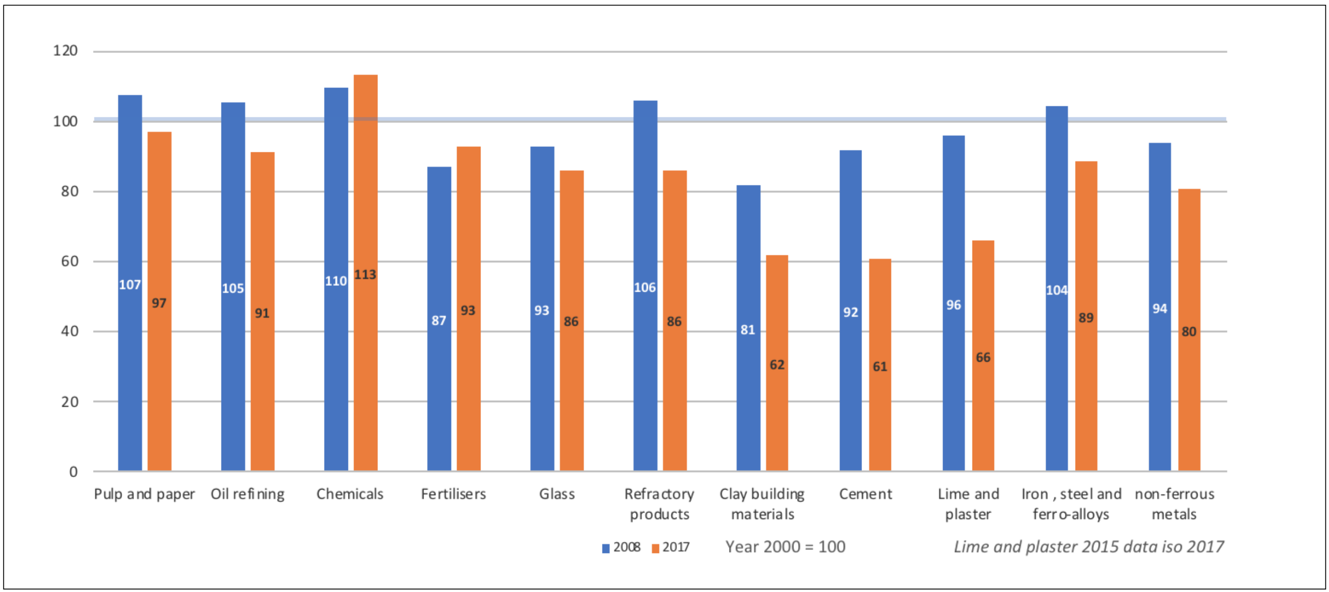

Figure 7: Change in production compared to 2000 (=100) in 2008 and 2017 (Source: Eurostat)

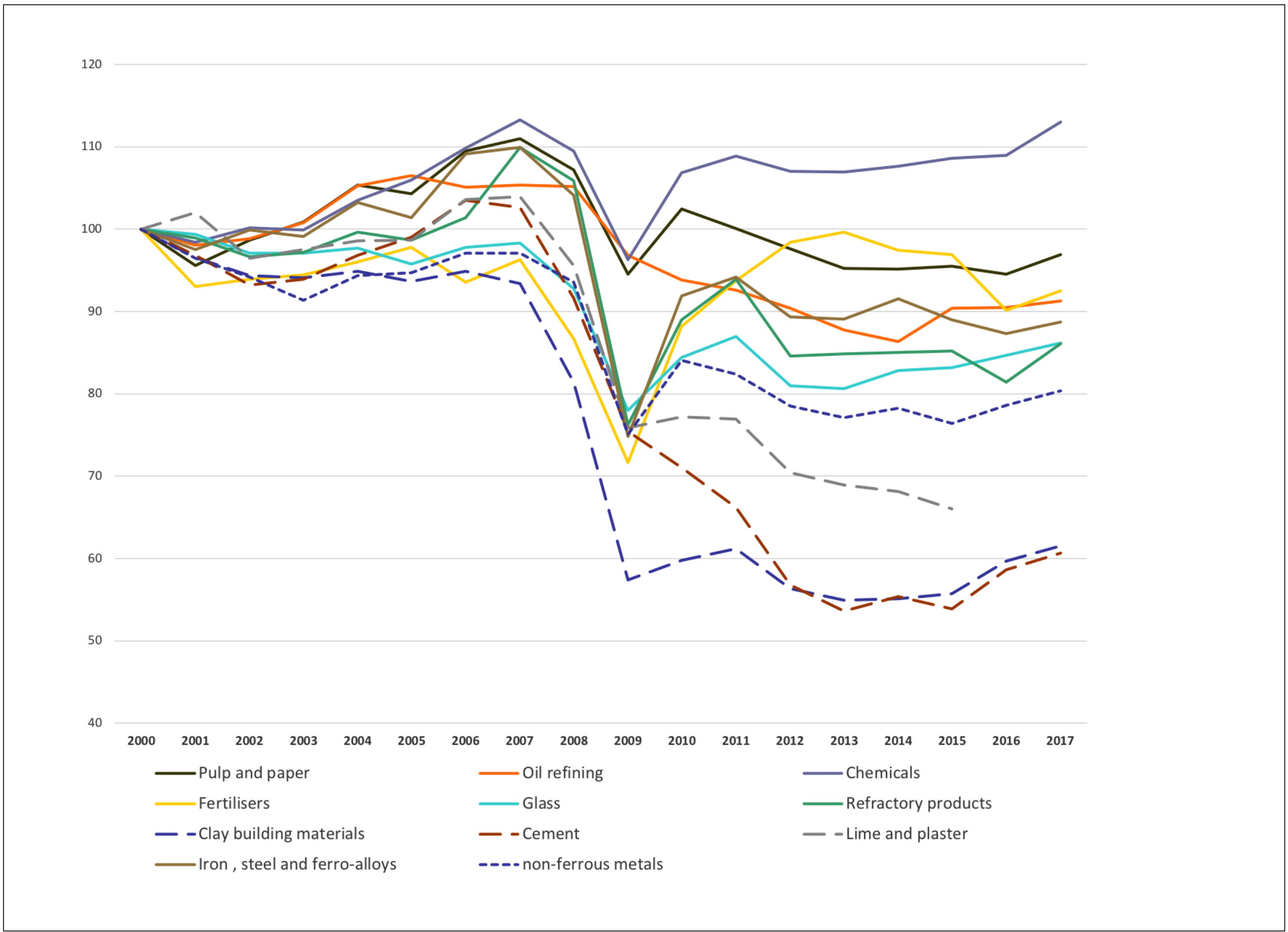

Figure 8: Change in production compared to 2000 (=100) time series 2000-2017 (Source: Eurostat)

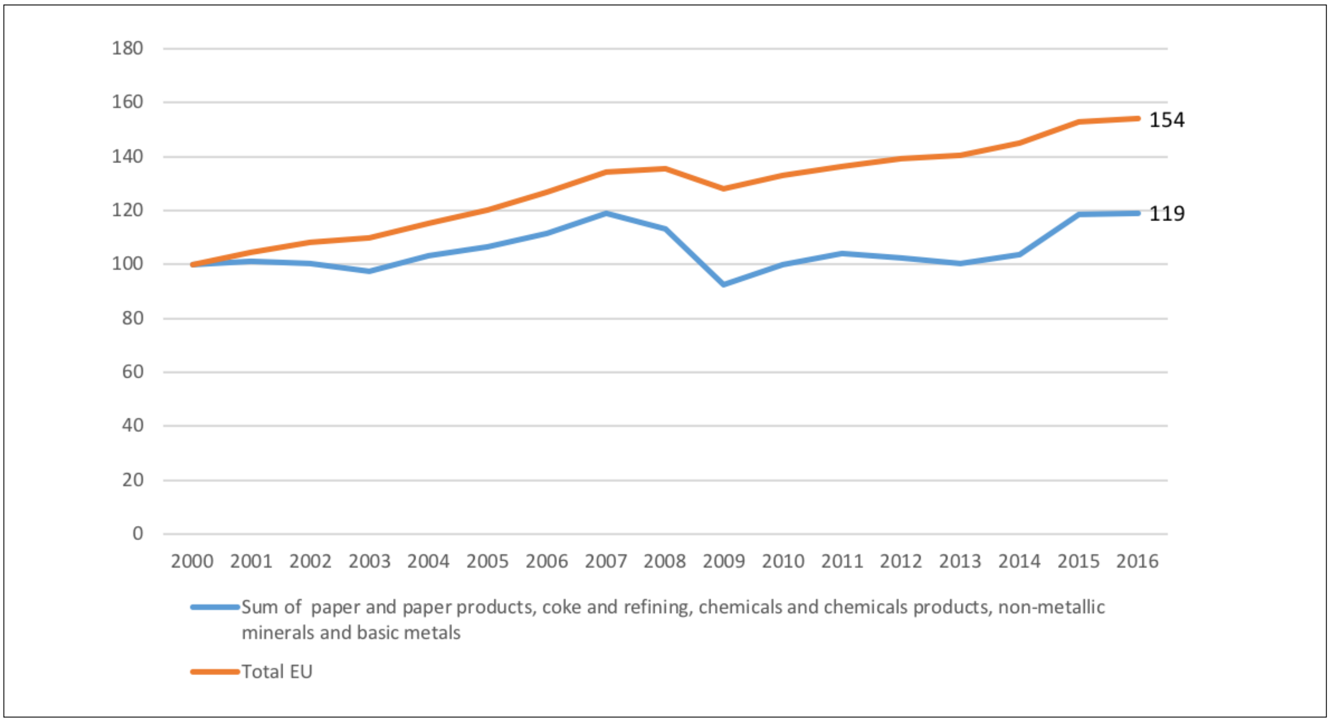

Figure 9: Relative evolution of EII gross value added and EU total gross value added between 2000 and 2016 (2000=100) (Source: Eurostat)

The EIIs, covered in this contribution, together employ nearly 1.5 million people (direct employment)[61] and are oriented largely towards domestic European consumption, forming an intricate value chain throughout the economy *(for more on value chains, see next section)*. The vast majority of the output is consumed within the EU internal market. For instance, the cement sector output stood at 169.1Mt in 2016 while consumption in the EU stood at 154Mt in the same year[62]. Imports outweigh exports in a number of sectors like steel, refining, glass, and ferro-alloys and silicon[63]. Ferro-alloys and silicon sector imports are particularly high at 73% of total consumption[64]. In the refining sector, demand even far exceeds throughput (refinery throughput in 2016 stood at 688Mt while refined petroleum demand stood at 753Mt)[65]. In the aluminium sector, imports were 48%[66]. Only in the chemicals, pulp and paper and ceramic sectors do exports exceed imports (EU ceramics sector had a positive trade balance of EUR 4.4Bn in 2015). Chemicals sector export value currently represents nearly 30% of total production value. In all other sectors, exports form a lower percentage of total production: 13.57% for steel, 17% for pulp and paper, and 8.93% for glass.

Trade intensity (Figure 10), as defined in the EU ETS Directive as the ratio between total value of exports to third countries plus the value of imports from third countries and the total market size for the European Economic Area (annual turnover plus total imports from third countries), is high amongst all the sectors with lower trade intensity (at EU level) for the cement and lime sectors[67].

61 Different industrial sector federations
62 CEFIC, 2017
63 UN Comtrade (No Date), Sector Data
64 EUROALLIAGES *(Sector Data)*
65 FuelsEurope, 2017
66 European Aluminium, 2016
67 Intensity of trade for cement is higher for production located at EU borders (e.g. Mediterranean).

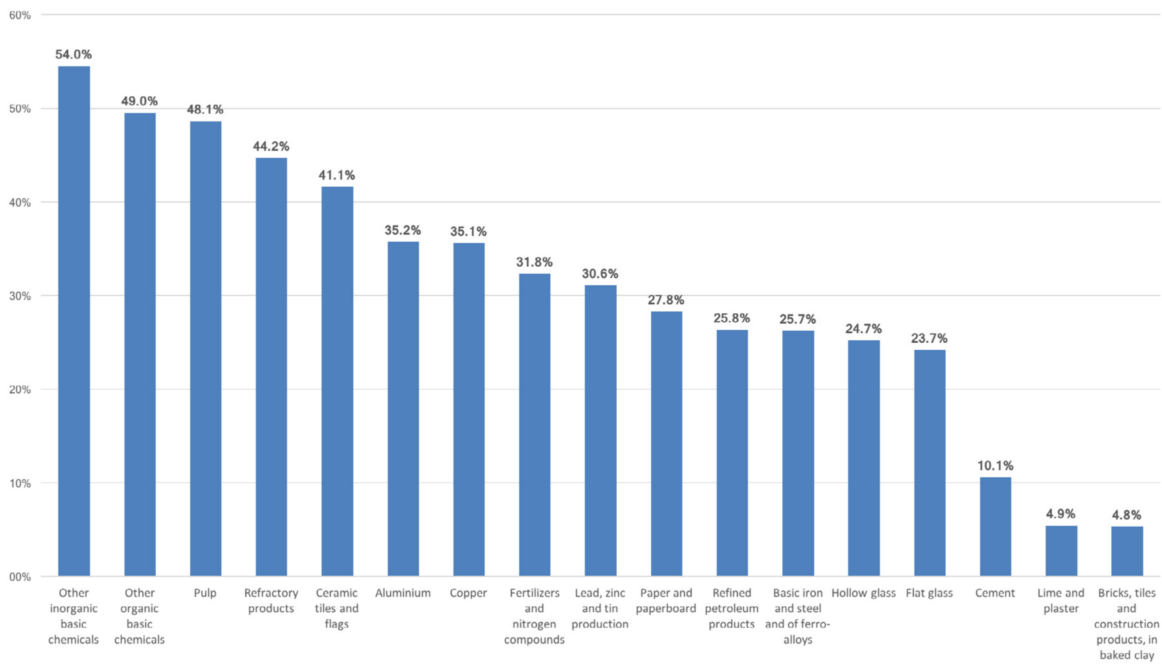

Figure 10: Trade intensity of energy intensive industries (Source: European Commission[68])

3.6. ENERGY INTENSIVE INDUSTRIES' VALUE CHAINS AND LOW-CARBON VALUE CHAINS

EIIs are of strategic importance to Europe's current value chains, critical to each other's value chains and at the forefront of low-carbon solutions.

The flow of materials to and from the EIIs forms a highly dense, integrated network with each other and every other sectors (rest of the economy). EIIs in fact enable the European economy and looking ahead, are needed to enable a carbon neutral Europe. The fundamental and even strategic links between EII and other sectors forms the basis of the manufacturing economy. EIIs enable almost all other sectors such as transport, buildings and constructions, defence, appliances, agriculture, food and beverages and so on. Figure 11 depicts the interconnectedness of the value chains between EII and all other sectors. But there are also important value chains connecting the EIIs themselves which proffer strong interdependencies. Some energy intensive sectors supply raw materials to other energy intensive sectors[69] and by-products of some EIIs are reused by other EIIs.

Finally, the products from EIIs are today indispensable to low-carbon solutions including from the perspective of adaptation to climate change consequences: energy-efficient buildings, decarbonised transport system (hybrid, electric and fuel cell vehicles including trains, ships and planes, roads, low-carbon liquid fuels and traffic infrastructure) renewable energy (solar PVs, wind turbines, thermal systems, etc.), battery storage, environmentally- friendly power distribution network with smart digital networks, 21st century low-carbon factories and infrastructure, 100% recyclable packaging, waste treatment, and energy and resource efficient modern communications and IT devices, and so on.

68 European Commission, No Date.
69 These products coming from EII and used as raw materials for other EII are key elements in the industrial value chain and their replacement has to be technically and economically viable which may be not always the case.

For instance

Transport:
A new car today is 22% more efficient than in 2007 and metals as well as light weight plastic materials help achieve this, together with high performance lubricants and fuels. Lime helps producing high strength steel for lighter cars and ferro-alloys are essentials to produce specialty steels. Concrete highways reduce vehicles fuel consumption by over 20%;

Buildings and appliances:
Lime helps producing high performing construction materials such as high strength cement and steel for sustainable housing and provides a longer life cycle to civil engineering applications, such as asphalts. Concrete thermal mass enables important HVAC savings reduces hot island effect in cities. Insulation through the use of foam, stone or glass wool, coupled with high performance glazing in buildings, have the potential to enable more than 80% energy savings[70][71] from buildings. Finally, energy efficient LED bulbs use a combination of metals and plastics.

Renewable energy and storage technologies:

- Solar photovoltaic panels and thermal systems use a combination of up to 22 non- ferrous metals, silicon, chemicals (e.g. organic electrolytes) and a specific type of flat glass. Innovation in light-weight flexible photovoltaic films is also enabled by the development of advanced polymers.
- 90% of a wind turbine's weight is comprised by metals components and each wind turbine contains over 14 non-ferrous metals. Wind turbines towers exceeding a height of 80 meters are also increasingly fully made of concrete. Concrete is also becoming a major component of offshore wind turbines (including floating wind turbines). Glass fibre is used to construct state-of-the-art tidal turbines capable of withstanding corrosive sea salt[72]. Finally, light weight chemical composites help increase the efficiency of the turbine through the introduction of longer blades.
- Batteries use different metals and alloys. They also include various chemical materials such as electrodes, electrolytes, membrane separator and battery trays.

70 Renovate Europe, No Date
71 Suschem, 2013
72 Sloan. J., 2012

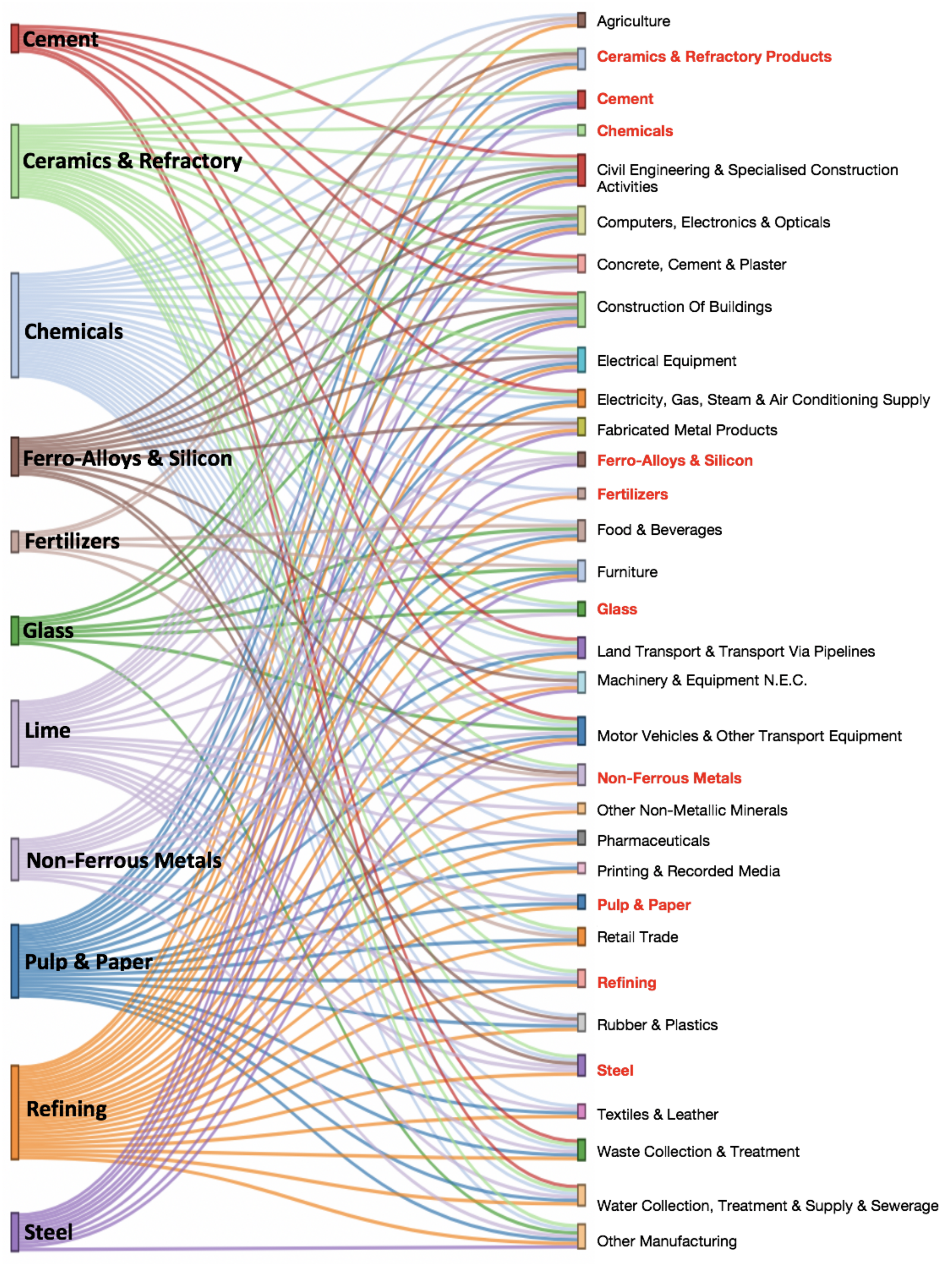

Figure 11: Value chain links of energy intensive industries to other sectors in the economy and other energy intensive industries (red)

KEY MESSAGES

SOLUTIONS SPACE

- Important progress has been made in the development of low-CO2 breakthrough technologies for EII processes. Continued European R&D support under different programmes together with private R&D initiatives led by individual companies played an enabling role in this progress. The gestation time of these breakthroughs is long and many of them have not reached industrial scale demonstration level.
- For each sector multiple technology options are being developed towards significant GHG reductions. It is important that all the above technology pathways get their fair chance in view of wide range of economics and technology readiness / development in the context of policy choices and financing strategies.
- Much higher levels of final electricity demand are expected if industrial low-CO_2 technologies are deployed across the EU.
- Transition to higher levels of electrification can create a virtuous cycle between the EU's renewable energy and industrial transition, under the right conditions.
- EIIs play an important role in the circular economy and this role will increase in the future in a conducive regulatory environment. Major economy-wide cost savings are possible.
- Industrial symbiosis, clustering and synergies with non-industrial sectors show potential for significant energy savings and materials efficiency.
- In the areas of energy transition and circular economy new business models are being explored. Together with increased digitisation and new skill-sets these can become important drivers for an efficient and competitive European industry.

4. SOLUTIONS SPACE

4.1. INTRODUCTION

This chapter will highlight that EIIs have been very active in researching developing solutions towards lower CO_2 emissions both in relation to their own emissions (footprint) and the emissions in other sectors of the economy through their products and activities (handprint). The latter includes further industrial symbiosis (between EIIs and with other sectors of the economy), materials efficiency and circularity, emerging business models in this context and a possible virtuous cycle between the EU's energy transition and the low-CO_2 transition of the EIIs.

4.2. INFORMATION FROM SECTORAL LOW-CARBON ROADMAPS, PATHWAYS & STUDIES

As part of the EII contribution to the European Commission's Strategy for long-term EU greenhouse gas emissions reductions, a list of relevant studies, roadmaps and pathways have been assessed together with the identification of the main messages and findings in these documents. The full list, including highlights of main messages from the studies can be found in an addendum to this document. The addendum also includes a comprehensive overview of more than 80 low-CO_2 technologies for all energy intensive industries (incl. brief description, technology readiness and where available impact on CAPEX, OPEX and energy use). The main findings on low-CO_2 technologies are presented in the next section.

4.3. OVERVIEW OF TECHNOLOGY SOLUTIONS TO REDUCE THE GREENHOUSE GAS FOOTPRINT OF EIIS

4.3.1. INTRODUCTION

The detailed technology assessment can be found as addendum to this document. While that assessment covers all technological options, a selection of main pathways applicable to most industries isl be presented below. These include:

- Further energy efficiency improvements and energy savings
- Process integration
- Further electrification of heat[73]
- Further electrification of processes
- Use of low-CO_2 hydrogen
- Valorisation of CO_2 (Carbon Capture and Utilisation)
- Use of biomass
- Higher valorisation of waste streams and materials efficiency
- Carbon Capture and Storage
- Selection of other technologies not (directly) covered by any of the above.

This section concludes by giving an overview of the likely application of these pathways across the different energy intensive sectors, the technological status pathways and how they can impact energy use, CAPEX, OPEX, infrastructure needs and bring possible co- benefits. Assessments related to materials efficiency and circular economy will be considered in section 4.5. It is important to note that the mitigation potential of the technologies presented is not always cumulative and that in some cases one technological pathway might exclude another.

73 And mechanical energy through electricity (e.g. electrical drivers)

4.3.2. FURTHER ENERGY EFFICIENCY IMPROVEMENTS AND ENERGY SAVINGS

Energy-efficiency improvements can reduce CO_2 emissions at a relatively low cost. However, on their own, these measures will generally not lead to deep emissions reductions. A global assessment by McKinsey & Co showed an economic potential of 15-20% reduction in fuel consumption in the longer term due to efficiency improvements[74]. In the EU this potential will be lower. An assessment *by ICF for DG ENER*[75] showed an economic potential of reduction in final energy consumption for EIIs between 5.8% and 12.7% compared to *Business As Usual* (BAU) energy consumption in 2050[76]. The technical potential is considered to be larger with savings ranging between 17% and 26%.

Sector	Economical potential (2 year payback - 5 year payback)	Technical potential (maximum energy saving potential)
Non-ferrous	12-12.7%	21%
Pulp and paper	5.8-7.1%	17%
Non-metallic minerals	6.6-7.2%	18%
Petroleum refining	8.5-9.5%	22.5%
Chemical and pharma	7.9-9.3%	22%
Iron and steel	8.6-9.4%	26%

Table 4: Energy savings potential in industrial sectors compared to 2050 BAU (ref. 2013) (Source: ICF, 2015)[77]

Achieving this deeper technical potential will require higher CAPEX investments e.g. replacements of major parts of existing production processes. In some cases, the payback of investments in some of existing technologies are far from attaining companies' typical financial criteria. At the same time high CAPEX expenditure will be required for new low- CO_2 technologies, including the replacement of existing processes. Because most of the EIIs have long investment cycles, it is therefore possible that investments in capital intensive energy savings measures might be forsaken in favour of radically new production processes such as the ones presented in the next sections.

4.3.3. PROCESS INTEGRATION

Existing fossil fuel based processes like iron and steel making processes can be modified by the integration of intermediate production steps combined with recycling or better internal use of generated process gases[78]. This integration of intermediate processes results in reduced use of carbon, and thus in reduced CO_2 emissions. Further considerable reduction of CO_2 emissions can be achieved by combining these integrated processes with Carbon Capture and Utilisation (CCU) and/or Carbon Capture and Storage.

4.3.4. LOW-CO_2 ELECTRIFICATION

Electrification of heat[79]

Electrified processes are already widely applied in basic materials industries (e.g. secondary steel, non-ferrous metals production and ferro-alloys & silicon). Electrification of heat demand can be applied across most of the basic materials industries. In some sectors such as ceramics, glass and paper production it seems the most promising measure for deep emission reductions.

74 Global estimate of potential. McKinsey & Co, 2018. p.25
75 ICF International, 2015
76 With 2013 final energy consumption as reference point
77 These data are not confirmed by the chemical and refining industry
78 Running projects in the iron and steel industry include among others HIsarna, IGAR (Injection de Gaz Réformé), PEM (Primary E nergy Melter)
79 This also includes further electrification of mechanical processes (e.g. compression)

In other sectors such as refining, steel, chemicals and cement, it can be a partial but important solution if economic hurdles are overcome. It will have to be used in combination with other technologies. The electrification of heat doesn't mitigate process emissions e.g. related to conversion of feedstock or raw materials.

With regard to heat demand, low temperature heat (e.g. below 300°C) can be relatively easily provided by electric boilers. Other technologies providing heat through electricity include electric arc, infrared, induction, dielectric, direct resistance, microwave and electron beam heating[80]. For electric furnace designs at higher temperatures (up to 1000°C), adaptation and scale up of electric furnace technology is needed. For temperatures above 1,000 °C, such as those required in cement kilns and for glass production, further research (currently ongoing) is required to develop industrial-scale electric furnaces[81].

Electricity based heating processes can, in some cases, be more efficient and economically interesting compared to fossil fuel based heating. However, using electricity originating from thermal generators (e.g. coal and gas) will significantly increase the primary energy demand due to conversion losses. In some cases, the integration of electric heating in existing processes will not require major changes (e.g. replacing gas with electric boilers for low temperature heat). In other cases, major investments in redesigning the production processes will be required. Given the deep integration of these industrial processes, any change to one part of the process will have to be accompanied by changes to other parts of the process[82]. Electrification of the furnace therefore necessitates adjustments to other stages of production. This will also impact the CAPEX because electrification of heat will not only be associated with the cost of installing electricity based furnaces but in some cases also the extra cost of reinforcing the infrastructure within the site (e.g. additional electrical infrastructure cost and grid connection, which can be significant) and the impact that electrification will have on other parts of the production processes[83].

Due to potential wide scale application, the mitigation potential of this technology can be significant for some sectors. Electrification would only make sense if electricity is produced without CO_2 emissions in a cost competitive manner (see section 5.3).

Electrification of processes

Electrochemical processes are currently deployed in the non-ferrous[84] and ferro-alloys & silicon industries (primary production) and in parts of the chemicals industry (e.g. chlorine production as part of the PVC value chain).

80 European Copper Institute & Leonardo Energy, 2018
81 McKinsey & Co, 2018
82 For instance, steam cracking process produces fuel gas, that is auto-consumed in the cracking furnaces. A new destination for this fuel gas will have to be identified in case the furnace is electrified.
83 For instance, the electrification of steam cracking will still lead to production of waste gases which are currently used as a fuel. In a fully electrified process other (non-trivial) solutions will have to be find for the use of these waste gases or the extent of electrification of the processes will be designed/limited to take into account this fuel gas balance.
84 International Zinc Association, 2012 | One sector, which has evolved greatly and embraced electrification in its production process is the European zinc sector. Presently, most zinc is produced using the RLE, full hydro process, accounting for 93% of the total pro duction. In 1990, full hydro represented only 62% of total zinc metal production. This process change occurring in the European plants has had a major impact on the CO_2 emissions pattern. The RLE, full hydro process has the lowest energy consumption and 94% of the consumed energy is electricity – with 84% of electricity consumed used in the electrolysis stage of the zinc refining process. Today, in the EU 27, electricity now represents 85% of all energy used in the production of zinc.

Further electrification of processes will only be applicable to some sectors such as steel and chemicals. Examples are steel electrolysis (including high temperature electrolysis), iron ore reduction with plasma (H_2). In the chemical industry, the utilisation of electrochemical processes[85] and development of other electricity-based processes (e.g. plasma, microwave, ultrasounds) are part of the options. Most of these innovative processes are early stage and at relative low technology readiness levels. In theory, some of these electrochemical processes could be more efficient (when comparing primary energy use) compared to currently used process technologies, but further optimisation of these processes would be required.

The emission reduction potential is high: in some cases emissions can come down to almost zero, but requires a fully decarbonised power sector. Hence, electrification would only make sense if electricity is produced without CO_2 emissions.

4.3.5. LOW-CO_2 HYDROGEN

There is significant and long-time experience of using H_2 in industrial processes (e.g. Haber- Bosch process for ammonia production, but H_2 is also extensively used in refining processes and as a product of coke production in integrated steelmaking). The main process for H_2 production currently used is steam methane reforming (SMR) in particular for ammonia production and for de-sulphuring and hydro-cracking in the refining[86] industry. It is one of the major CO_2 emissions sources in the chemicals industry. A likely route for low-CO_2 H_2 production is electrolysis, but alternative routes[87] to low-CO_2 H_2 production should also be considered, including methane pyrolysis, water photolysis and the combination of standard SMR with carbon capture and storage (see section 4.3.8)[88].

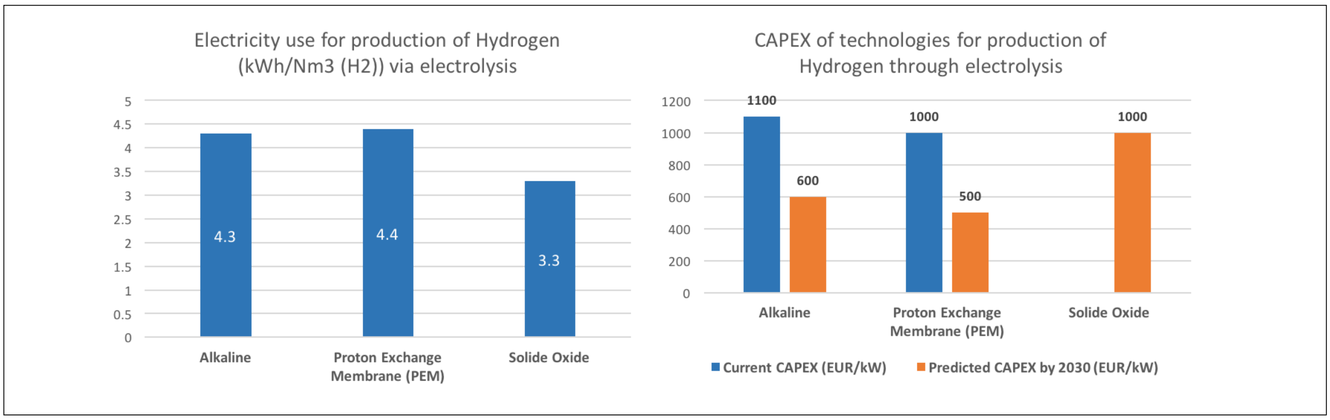

Figure 12: (Left) Energy demand (kWh/Nm³ H_2) and (right) CAPEX (EUR/kW) for the three H_2-electrolysis routes. (Sources: DECHEMA, 2017[89]; CEFIC; VUB-IES[90])

There is a diverse range of application of H_2 in industrial processes in particular in the refining, chemicals and steel industry. In chemical processes it can be used to produce low- CO_2 ammonia and (in combination with CO_2) to produce methanol and other basic chemicals such as olefins.

85 E.g. ethylene production (with CO_2 utilisation) and plasma reforming of methane or waste gases towards syngas.
86 FuelsEurope (*Sector Data* – Concawe) | H_2 is used in the refining process to remove the Sulphur of the final products (e.g. Diesel 10 ppm S) or to maximize the conversion of heavier fractions into more valuable products (Hydro-cracking). H_2 ad-hoc production accounts for ≈ 15% of the total CO_2 emissions from EU refining system.
87 IEA, 2017b .p.8 for the presentation of a broad portfolio of hydrogen production technologies.
88 Sintef, 2017 | A comparison of future Hydrogen production costs by Sintef and the Zero Emissions Platform (ZEP) for electrolysis, SMR and SMR with CCS projects a convergence of production costs for these technologies between 2040 and 2050 at carbon prices between 50 EUR/t to 150 EUR/t, CCS costs at 60 EUR/t CO_2, electricity cost between 0.050 and 0.080 EUR/kWh, electrolyser operating time above 4000 h/pa and gas prices between 0.044-0.068 EUR/kWh.
89 Dechema, 2017
90 VUB-IES, 2018

Similarly, H_2 can be used as a feedstock (together with CO_2) to produce (synthetic) fuels[91] or used as a direct product (final fuel). In primary steel making, H_2 can be used as a reducing agent in DRI or smelting processes. When even higher melting temperatures are required, e.g. for the production of some ferro-alloys and silicon, this technology might not be applicable.

While alkaline electrolysis H_2 production has been commercially available for a long period the TRLs of other innovative H_2 production processes and in particular their use in production of basic materials (e.g. chemicals and steel) have not reached commercialisation stage but pilot plants are under construction in the EU. Most of the CAPEX will be related to the production of H_2 itself. The OPEX will also depend on the efficiency of electrolysis and the cost of (renewable) electricity. Electricity demand will be higher in case of H_2 electrolysis options[92]. Infrastructure development will be important (high voltage power for onsite production or transport infrastructure for H_2). This will be further discussed in sections 5.4 and 5.5.

The mitigation potential is high (beyond 80% reductions in most cases), but requires a fully decarbonised power sector for electricity based H_2 production.

4.3.6. VALORISATION OF CO AND CO_2 THROUGH CARBON CAPTURE AND UTILISATION (CCU)

Utilisation of CO_2 as carbon feedstock is known in the chemical and fertiliser industry (e.g. urea, methanol and other products). CO_2 can be used as an alternative source of carbon for the production of a wide range of chemicals from basic chemicals to fine chemicals and polymers through new production routes. Many of the high volume chemicals and fuels could be produced with (CO or) CO_2 combined with low-carbon H_2, however economical pathways might prove challenging with current technologies based on H_2 from water electrolysis while alternative technological pathways (e.g. use of other co-reactants instead of H[93] or blast furnace waste gas to produce ethanol via biological conversion) could be more viable. Processes using H_2 from electrolysis as co-reactant will often also need additional low-CO_2 electricity.

Interest in CCU has grown over the past years across different sectors (e.g. cement, steel and chemicals). For example, waste gases from iron and steel production can be used to produce basic chemicals (e.g. bacterial conversion to ethanol). The potential of using CO (with added H_2) from iron and steel production waste gases towards high value chemicals is high, in particular due to the efficient conversion process of ethanol to ethylene.

Power-to-fuels (also called e-fuels, produced from CO_2, renewable energy and water) are an important means to progressively reduce GHG emissions from transport. E-fuels in liquid form (also known as Power-to-Liquid or PtL) especially, have several advantages with respect to other technologies for transport decarbonisation: the use of existing infrastructures, the compatibility with the current vehicle fleet, the suitability for use in heavy duty road transport, aviation and shipping, and the long-term storage of renewable energy.

91 A technology pilot plant in Dresden, Germany is producing e-diesel from water, CO_2 and renewable electricity (see: sunfire.de).
92 With exception of water photolysis and to limited extent for methane pyrolysis.
93 E.g. production of CO_2-based polyols

CO_2 utilisation through the carbonation of solid raw (waste) materials (e.g. concrete, slags, ...) or concrete curing is advancing well as a way to valorise CO_2 but also cement and concrete production is moving ahead with utilisation (e.g. through carbonation) of CO_2. The commercialisation of these processes has started. The potential of these processes is significant (e.g. up to 25% of emissions in cement production) and additional energy needs are much lower compared to for instance H_2 based CCU routes.

Cost competitive access to CO_2 is important for all CO_2 valorisation routes and applications. Often high purity/uncontaminated sources of CO_2 are required. Separation and purification technologies are therefore needed for the valorisation of CO_2 from industrial streams (and from air). The level of purification needed depends on the input stream and the CO_2 valorisation route. A more competitive access to CO_2 from industrial point sources will improve the business case of CO_2 valorisation in many cases and requires:

- More energy efficient CO_2 separation and purification solutions with low capital intensity and operational cost,
- Adaptation of the level of purification according to the chemical conversion process based on the minimum concentration/maximum impurities of CO_2 streams that the different conversion processes can tolerate.

As with any other technology, the mitigation impact of CO_2 utilisation and valorisation technologies requires an appropriate evaluation based on a qualified Life Cycle Analysis. All contributions to the carbon footprint have to be taken into account in order to quantify avoided CO_2 emissions by conversion of CO_2 as an alternative carbon source as compared to conventional production pathways. System boundaries for the evaluation have to be carefully defined for each case. For instance, for a specific chemical, the net CO_2 emissions avoidance can be evaluated on a cradle-to-gate basis by comparison of CO_2-based production to the standard production, since the emissions during the use phase and end-of life of the product are independent from the source of carbon feedstock. Where the life cycle of the product is affected, or where the carbonation of the product in use is reduced, a cradle-to-gate approach is inappropriate and a whole life cycle approach is required.

4.3.7. BIOMASS

Biomass (e.g. wood, agricultural and forestry waste and residues) is a key raw material or feedstock for the paper and silicon industries and an increasingly important raw material for the chemicals and refining industries. Biomass is also used as a partial replacement of coal as reductant in ironmaking.

Biomass is also being used as an energy source in most sectors, but at lower levels compared to other energy inputs due to the limited available quantity. Over the past decade, a lot of experience has been gained in the EU with the production of biofuels. Second generation biofuels (e.g. cellulosic ethanol) are now reaching commercialisation stage.Other advanced biofuels are the subject of intense R&D activity and early deployment, as in the case of biofuels from algae[94].

94 ExxonMobil., n.d.

Many basic and specialised chemicals, including new innovative products can be produced using bio-based feedstock, either as products with identical chemical formulas or as products with similar performance. The paper sector can become an important provider of bio-based chemical feedstock products (e.g. lignocellulose) and of higher value applications like carbon fibres and batteries. Bio-ethanol can become an interesting platform molecule for part of the high value added chemicals value chain[95]. Some processes (e.g. propylene from biomass) do however require a significant amount more energy compared to fossil feedstock based routes. Further R&D is likely needed to optimise production of bio-ethanol and of innovative processes that produce basic and/or fine chemicals using bio-based materials.

Biomass can only be a partial solution given that the two key materials to produce bio-based materials available in Europe (i.e. straw and forestry products) would provide for only 1.4 to 2.6 EJ[96] which is less than half of the energetic and non-energetic final consumption by the chemical sector alone (5 EJ in 2016) and hence would not even include either existing value- adding uses of these bio-based materials or possible new demand from other industrial and non-industrial sectors. However, the development of processes for the utilization of other types of biomass (e.g. algae and non-food / non-ILUC plants) may soon open new possibilities for low-carbon fuels production. Research is underway to establish estimates on future biomass demand and supply in the EU[97]. However, at this time, results are absent or inconclusive e.g. due to rough and fragmented sources. Further research is required to ascertain reliable quantified estimates.

Supply and supply chains of biomass (as feedstock for basic materials production) can therefore become an important bottleneck. In particular, because there can be significant demand side competition for biomass for (renewable) power and municipal heat production. Biomass from waste provides an important energy source to the cement and other EII sectors but faces undue competition through subsidised bio-energy generation.

Overall, given the limited supply of biomass together with the existing industrial biomass demand and demand from other non-industrial sectors, biomass cannot be the panacea for deep GHG emissions reductions in EIIs.

4.3.8. HIGHER VALORISATION OF WASTE STREAMS AND IMPROVED MATERIALS EFFICIENCY

Higher valorisation of different types of waste streams and improved materials efficiency will be relevant across most industries. The fertilizers industry is already an important consumer of industrial by- or waste products. The cement industry also valorises major quantities of waste streams (municipal and industrial waste) in its processes as well as by- or waste products from other industries (e.g. granulated blast furnace slag and fly ash).

In the chemical industry there is a significant potential for further chemical recycling of major product waste streams (e.g. plastics, rubber, textiles and silicones)[98].

95 E.g. for the production of ethylene.
96 Estimates from CEFIC&ECOFYSs, 2013,p. 112
97 JRC, 2018
98 Accenture, 2017, p.8

Plastic waste is in particular a key alternative feedstock which will develop alongside the technology advancements in chemical recycling. Technical hurdles include the lack of pure waste streams and difficulties removing coatings and other additives. The potential CO_2 emissions saving by producing plastics from plastic waste can vary significantly depending on the type of plastics and their applications (in many cases it can save up to 50 % in GHG emissions compared to a fossil fuel based plastic)[99]. New technologies make it possible to turn municipal waste into an important feedstock for the chemical industry with the potential to mitigate GHG emissions[100].

Steel and non-ferrous industries can see an increased valorisation of scrap metals by reducing the contamination of scrap flows. For steel, the main challenge will be the reduction of copper contamination of scrap steel (which results in down cycling of high quality steel to construction steel). This can be achieved by (challenging) new technological innovations that allow the extraction of copper from molten scrap steel but also designing final products to be recycled more easily, by improving shredding and by scrap sorting processes. In glass production, there is the potential to increase the use of recycled glass as raw material. In particular, with regard to flat glass, higher recycling rates are possible in the future (depending on construction waste regulations, practices and development of reverse logistics).

Finally, low temperature (waste heat) which is present in most energy intensive processes can become an important energy source for other sectors in the economy e.g. via district heating (see also section 4.4).

4.3.9. CARBON CAPTURE AND STORAGE (CCS)

Carbon capture and storage can become an interesting mitigation option for large point sources (+ 1 Mt) or clusters of large point sources of CO_2 emissions, in particular, for process emissions with a high CO_2 concentration (e.g. steam methane reforming). It hence can be a very relevant option for cement & lime, steel, chemical manufacturing and refining. Over the past years important initiatives have been launched in the EU to develop the technology further in the cement, lime, refining and steel sectors. But CCS is not a mature, deployed technology: no large-scale, post-combustion carbon capture plants now operate at industrial sites[101 102].

In general, industrial process emissions (if they have a large CO_2 concentration in exhaust gas streams) can be more interesting to be captured and stored compared to CCS in other sectors. A very high CO_2 concentration would negate or reduce the need for technologies that capture CO_2 out of diluted flue gases[103] and hence lead to less costly CCS for these processes. The total cost of CCS can range from EUR 22/tonne CO_2 to EUR 164/tonne CO [104].

99 A quantified overview on all types of wastes and recycling processes would need to be performed as today many studies only gi ve results on specific cases. It is expected that the current JRC study on developing a LCA modelisation for alternative feedstocks should give a more precise quantification. This will also allow a prioritization in the developments of such technologies and in the use of waste based plastics.

100 An upcoming project "Waste2Chemistry" which will be deployed in Rotterdam, aims at producing methanol from municipal waste, with estimated CO_2 savings of 135kT per year.

101 McKinsey & Co, 2018. | The slow development of CCS is mainly due to economic barriers and not necessarily related to technolo gical issues. At this moment the most economically viable CCS projects around the world all are linked to enhanced oil and gas recovery.

102 Norcem, n.d., | One of the most advanced industrial CCS demonstration projects in Europe it the NORCEM Brevik CCS project in Norway.

103 E.g. oxyfuel and post-combustion capture technologies.

104 Mckinsey & Co, 2018. | This includes the costs of capturing CO_2 from exhaust gases, transporting captured CO_2 to a storage site, and storing it. Global CCS institute, 2018. | The costs of transporting and storing captured CO_2 range from EUR 6/ton CO_2 to EUR 30/ton CO_2, depending on the distance from the site where the CO_2 is captured to the storage location, the type of storage location, and the availability of existing storage infrastructure (as might be found at natural gas production sites, for example).

At the lower end of this cost range, production processes with a high concentration of CO_2 in in exhaust streams will be found such as ammonia (steam methane reforming process) with up to 95-100% CO_2 concentration, and ethylene oxide production with 30-100% CO_2 concentration[105].

Ideally CCS would be combined with advanced process integration or with new processes that generate important co-benefits (e.g. purity of products or energy savings). This would allow the additional costs of CCS to be off-set by one or more co-benefits related to innovative processes. Interesting examples of breakthrough process technologies that would have these co-benefits are the HIsarna[106] steelmaking process and the Leilac[107] direct separation CCS process for lime (and cement clinker) production, currently being developed in Europe. Both new processes will, due their high CO_2 concentration in exhaust streams and other efficiency advantages, also be at the lower end of the above mentioned cost range.

At the higher end of the CCS cost range is the application of CCS in refining and oxy-fuel and post-combustion based CCS in cement production. For refining, recent simulations of retrofitting CCS in integrated oil refineries estimate the cost of CO_2 capturing at EUR 138- 185 t/CO_2 avoided[108]. In cement production, the use of CCS would increase production costs by 25-100% (and requires substantial investments and additional use of electricity)[109].

For sectors with smaller point source CO_2 emissions (e.g. below 1Mt CO_2-eq p.a.) CCS is unlikely to be an option unless these installations are located close to other large emitters or are part of a larger industrial cluster.

The mitigation potential is on average 80% compared to current processes, but could go up to 95% in some cases.

Beyond the technological and cost challenges there are other important factors that will influence the practical application of CCS, for instance due to legal provisions[110] preventing deployment of CCS as well as possible lack of public and political acceptance of both storage and transmission.

4.3.10. OTHER TECHNOLOGIES AND OPTIONS

The nine categories of low CO_2 breakthrough technologies and techniques mentioned above do cover most but not all options for deep mitigation in basic materials industries and the specific link with digitisation.

In particular, for cement and aluminium production, other important options are being implemented or considered.

105 Global CCS institute 2018 & UNIDO 2010
106 Tata Steel, n.d.
107 Leilac Project, 2018. | shows this technology to be very promising from an economic perspective (no energy penalty for CO_2 capture, comparable CAPEX to existing process technologies and likely lower OPEX, can be no-regrets option for cement and lime industry.
108 IEA, 2017a, p.7
109 Cembureau, 2013, p. 43 | Oxyfuel and post-combustion technologies
110 Some member states have prohibited the underground storage of carbon dioxide.

For cement production there exists a wide range of options to use cement types with low clinker content and is research ongoing on new binding materials as alternative binders to Portland cement clinker[111]. However, most of these alternative materials have restrictions when it comes to their availability and/or applicability in types of concrete. Advanced grinding technologies could decrease the electricity intensity of cement production beyond current best practice levels and provide means to manage electricity demand more flexibly. They include contact-free grinding systems, ultrasonic-comminution, high voltage power pulse fragmentation, and low temperature comminution[112]. Finally, more carbon-efficient concrete can be achieved through optimisation of concrete mix design including a more efficient packing of aggregates, sand and cement.

In primary aluminium production, there are technologies which are being researched and developed that would reduce the direct emissions (from carbon anodes) and the energy used in the electrochemical process. This includes the development of inert (non-carbon) anodes that do not lead to direct CO_2 emissions and wetted cathodes that improve the electrical contact between molten aluminium and the cathode. Wetted cathodes could reduce energy use by approximately 20% compared to conventional carbon cathodes. If inert anodes are developed, a possibility for reduced energy consumption is the development of multipolar cells for primary aluminium production which have the potential to reduce energy consumption substantially due to lower operating temperatures and higher current densities. Since such cells require inert anodes, process emissions from the use of carbon anodes would also be reduced. All of these technologies have not yet reached the demonstration stage.[113]

Finally, enhanced digitisation can lead to optimised product and process design and production, resulting in emissions reductions[114] by reducing energy and raw material consumption, enabling the tracking of materials from source to end of life, shortening value chains and allowing faster response to customer demands and specifications. Services added onto a product might hence create higher resilience and competitiveness due to the unique value proposition for customers. It would also open up new opportunities for business models based on digital technologies such as cloud computing, big data, the new industrial internet, applications, smart factories, robotics and 3-D printing, leading to advanced manufacturing or integrated intelligent manufacturing[115].

4.3.11. EU INITIATIVES SUPPORTING INDUSTRIAL LOW CO_2 TECHNOLOGIES

Many of the technologies assessed in this contribution and presented in the addendum to this contribution have been enabled through EU (and national) R&D support. Important EU programmes include the EU's 7th framework programme for innovation, Horizon 2020 (including the Bio-Based Industries PPP), Sustainable Process Industry through Resources and Energy Efficiency (SPIRE PPP), Sustainable Industries Low Carbon (SILC), the EU LIFE programme and the EIB's Innovfin. Many of the low-CO_2 technologies under development have a long lead-in time to reach higher TRLs, and most face either a risk of not being able to bridge the gap from pilot to demonstration to commercialisation stage or of not getting enough support from investors in the absence of a stable long-term policy framework.

111 CSI/ECRA, 2017
112 IEA, 2018
113 Ibid.
114 World Economic Forum, 2017
115 ESTEP, 2017

The forthcoming EU ETS innovation fund, with its focus on supporting industrial low-CO_2 innovation, should give some of these technologies the support to reach demonstration level. See also section 5.2 on further R&D challenges.

4.3.12. SUMMARY OF TECHNOLOGY OPTIONS

The table below gives a basic overview of the potential to apply the main technology pathways mentioned above at sectoral level. The goal is to visualise pathways that apply across multiple sectors, but this not does imply that the actual pathways will follow this assessments (e.g. due to further R&D barriers and other framework conditions not materialising (see chapter 5). The mitigation potential of the technologies presented is not always cumulative and in some cases one technological pathway might exclude another one.

	Electrification (heat and mechanical)	**Electrification (processes: electrolysis/ Electrochemistry excl. H2)**	**Hydrogen (heat and/or process)**	**CCU**	**Biomass (heat and feedstock)/ biofuels**	**CCS**	**Other (including process integration)**
Steel	**xxx**	xx	xxx	xxx	x	xxx	Avoidance of intermediate process steps and recycling of process gases: xxx Recycling high quality steel: xxx
Chemicals fertilizers	xxx	xxx	xxx	xxx	xxx	xxx(*)	Use of waste streams (chemical recycling): xxx
Cement Lime	xx (cement) x (lime)	o (cement) o (lime)	x (cement) x (lime)	xxx (cement and lime)	**xxx** (cement) x (lime)	xxx (cement and lime)	Alternative binders (cement): xxx Efficient use of cement in concrete by improving concrete mix design: xxx Use of waste streams (cement): **xxx**
Refining	xx	o	xxx	xxx	xxx	xxx	Efficiency: **xxx**
Ceramics	xxx	o	xx	x	x	o	Efficiency: **xxx**
Paper	xx	o	o	o	**xxx**	o	Efficiency: **xxx**
Glass	xxx	o	x	o	xxx	o	Higher glass recycling: xx
Non-ferrous metals/alloys	**xxx**	**xxx**	x	x	xxx	x	Efficiency: **xxx** Recycling high quality non-ferrous: xxx Inert anodes: xxx

o: Limited or no significant application foreseen
x: Possible application but not main route or wide scale application
xx: medium potential
xxx: high potential
xxx: *Sector already applies technology on large scale (can be expanded in some cases)*
(*) in particular for ammonia and ethylene oxide[116]

Table 5: Overview of low-CO_2 technology potential for energy intensive sectors

It is important to stress that the identified technical potentials will have to be assessed in view of technological developments, evolution of energy commodities, as well as of resources availability.

116 Global CCS institute 2018 & UNIDO 2010

For instance, high potentials for biomass are not applicable for all sectors at same time, as there is not sufficient unused biomass available/growing.

The next table brings an assessment across the main pathways identified in terms of technology status, impact on energy use, CAPEX (relative to investments in current state of the art), OPEX (relative to current operations), infrastructure needs and possible co-benefits.

	Technology status	**Energy use - compared to current operations**	**CAPEX – relative to conventional technologies[117]**	**OPEX – compared to current operations**	**Infrastructure needs[118]**	**Possible co-benefits**
Electrification heat	High TRL except for high T furnaces (glass, cement)	Higher electricity demand but primary energy use can be lower	Depends (replacement of boilers relative low additional CAPEX, (high T) furnaces major investment)	Depends on (favourable) electricity vis-à-vis natural gas prices and efficiency improvements from electrification.	medium	Higher potential for electricity demand response. Possible energy savings.
Electrification processes	In most cases not reached demonstration stage	Higher electricity demand but primary energy use can be lower	High	Highly dependent on electricity prices	Low/medium (might be need for more/ upgraded HV connections)	Higher potential for electricity demand response
Process integration	Move towards pilot and demonstration plants	Medium/high	Medium (unless combined with CCU or CCS)	higher	Medium (unless combined with CCU or CCS)	Recycling/ process internal use of generated process gases
Hydrogen	Mov towards pilot and demonstration plants	High electricity consumption for electrolysis based production	High	Higher (dependent on electricity prices)	High (unless H_2 production happens on site)	Possibility of power storage (e.g. use of ammonia as carrier)
Biomass	Diverse, move towards pilot and demonstration plants for newest technologies	Can be notably higher	High for feedstock applications (new process technologies) Low/medium for fuel applications (compared to e.g. natural gas based furnaces)	Higher for feedstock applications Comparable to conventional for some fuel applications (depends on price of biomass)	Medium/high (need for new and reliable logistics chains for sustainable biomass from within and imported into the EU)	Industrial symbiosis (e.g. use of biomass waste streams)
CCU	Moving towards commercialisation for carbonation and synthetic fuels. Other processes see move towards pilot and demonstration plants.	Can be very high for H_2 based routes. Limited for carbonation and mineralisation.	High (but lower for some carbonation technologies)	Can be High (esp. when H_2 from electrolysis is required. depends on renewable electricity price). Limited for carbonation/ mine ralisation.	High	CO_2 becomes resource instead of cost
CCS	Move towards pilot and demonstration plants	Will be higher	High[119]	Higher[120]	High	Possible process integration benefits

Table 6: Assessment of main technology options vis-à-vis technology status, energy use, CAPEX, OPEX and infrastructure needs

117 On site CAPEX only
118 Internal (site level) and external infrastructure needs.
119 HIsarna (steelmaking) and Leilac (lime/cement) projects expect CAPEX similar or lower compared to current technologies.
120 HIsarna, Leilac and CCS applied to steam methane reforming (ammonia) can have relative low additional OPEX due to high CO_2 concentration in exhaust streams.

4.4. INDUSTRIAL SYMBIOSIS AND SYNERGIES WITH NON-INDUSTRIAL SECTORS

As shown in section 3.3 on value chain analysis, basic materials industries have a strong connection with each other. The refining sector and petrochemical industry are even physically integrated through large process installations (e.g. naphtha crackers). Primary steel productions deliver one of the important constituents (i.e. granulated blast furnace slag) for the cement industry. Silica fume, which is a by-product of silicon and ferro-silicon, is added to concrete in construction, which contributes to a reduction of cement use while providing better performances. Lime forms an essential raw material for steel, paper and glass production and has played a vital role in reducing damaging emissions of sulphur dioxide. Cement and fertilizers contribute to recycling and recovering waste and by products from other EIIs. Industrial symbiosis is also already used extensively at site level with multiple production installations (e.g. exothermal processes delivering heat to processes requiring additional energy). There are examples of EIIs delivering waste heat to other industries or sectors of the economy (e.g. paper production to automotive or waste heat used for district heating).

The technology assessment (section 4.3) indicates that industrial symbiosis will become more prominent as sectors seek to reduce GHG emissions. Waste gases from primary steel production can become the feedstock for the production of high value added chemicals[121]. Steel slag, a waste product from blast oxygen furnaces, can be used as the main constituent in cement for use in bricks[122]. The pulp and paper and chemical sectors will likely also align more with forest fibre derived bio-based products, becoming feedstock for a wide range of chemical products.

A broad and EU-wide assessment of the future potential of industrial symbiosis was undertaken by the EPOS SPIRE project in 2016. It succeeded in mapping all European industrial sites of cement, steel, refining and chemicals to systematically assess the geographic dimension of industrial symbiosis. Five hotspots were identified in Europe. The largest one covers Northern France, Belgium, the Netherlands, Luxembourg and Western Germany and includes 20% of total European industrial sites while 40% of the potential couples of sites lie within a 200km radius. Northern Italy also emerged as a hotspot, especially due to the presence of electric arc furnaces and cement plants. Other medium hotspots were identified around Krakow, Bilbao and the UK Midlands. In between, the density of industrial sites is lower and more stretched.

121 The amount in Europe would suffice to supply the production of 55 Mt methanol (Dechem a, 2017) or the majority of ethylene production in Europe (AcelorMittal – Steelanonal)
122 Vito, 2014

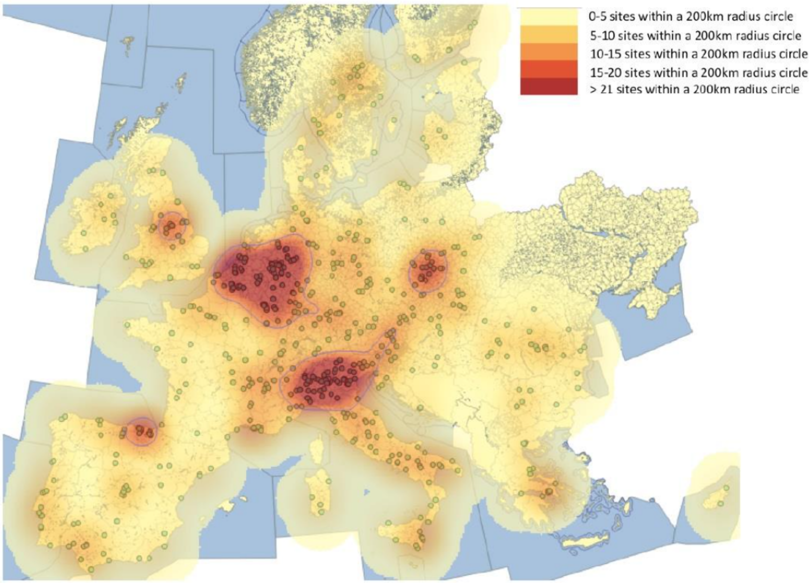

Figure 13: Concentration of industrial sites in Europe (source: EPOS WP6 EPOS Tool market study by STRANE, 2016)

An in-depth techno-economic assessment was carried out on a selection of technically credible set of resources for potential synergies. The synergies that were found economically credible could have a truly sizeable impact. For instance, the valorisation of tar sludge from steel to cement could potentially represent 19 TWh/year, i.e. 1% of the European annual solid fuel consumption or 24% of the annual energy consumption of the cement sector in Europe. Another example, the mutualised treatment of dusts from all considered sectors would recover precious metals and critical raw materials representing around 1% of the world production, therefore bringing a major relief to the resource independency of Europe. District heating appears as a particularly promising potential for the considered sectors. They could in theory produce 317 TWh/year of waste heat to be used for district heating, to be compared with the current consumption of district heating of 225 TWh/year. 52 million inhabitants live less than 8 km from a site representing one of the considered sectors. Developing district heating could in theory replace the consumption of fossil fuels, representing 200 Mt CO_2 savings per year (4% of EU emissions). But it must be noted that this is a theoretical potential. Developing a district-heating network requires many conditions to be viable (e.g. long winter seasons, population density, distance to populated areas, acceptability and a favourable topology)[123] and needs large low level heat draw points and customers. Locations and demand profiles do not necessarily always match either.

4.5. CIRCULAR ECONOMY AND MATERIALS EFFICIENCY

As shown in section 3.4, most EII's have already incorporated circularity and materials efficiency in their business models to a large degree (e.g. through industrial symbiosis - see section 4.4 above). For most basic materials, enhanced circularity will become more important over the next decades as a strategy to reduce emissions, reduce energy use[124], maintain security of supply (in some cases), and enhance production and growth while reducing costs.

123 Strane, 2016
124 Eurometaux *(Sector Data)*. | For example, Aluminium recycling is upto 95% less CO_2 intensive vs primary aluminium making while Copper recycling is upto 80% less CO_2 intensive vs primary.

There are factors which can help achieve higher levels of circularity in all the EII sectors, like the reduction of losses in the production of semi-finished and finished products, the prevention of down-cycling to lower-quality materials (in particular as concerns certain non- ferrous metals, ferro-alloys and plastics)[125 126], the reduction of contamination of end of life materials streams[127], the development of new and more efficient separation technologies (for instance, to remove copper from steel which would allow up to 90% recycling of steel)[128], and reduced recycling in mixed streams which results in higher losses[129 130].

The potential in the chemicals sector for higher levels of circularity is also important. For example, increased reuse of end user products, mechanical recycling and chemical recycling can bring back 24 Mt out of the 106 Mt chemicals in circulation in Europe[131]. European companies are currently researching higher levels of mechanical and chemical recycling. However, more R&D will be required to realise the full potential enough to close the loop.

There are two vast yet mostly underused waste streams which can be exploited to achieve exponential levels of circularity: e-waste and construction and demolition waste. In the non- ferrous and ferro-alloys sector, e-waste can become a key source of raw materials, lessening the sectors' import dependency. In Europe, valuable materials recovered or lost in the EU's scrap vehicles, batteries, computers, phones, gadgets, appliances and other high tech products discarded annually equal to roughly 18 million tonnes[132 133]. Only one third of Europe's electronics waste is collected and recycled through the proper channels[134]. Some European companies have shown global leadership in tapping into this market but face stiff competition from recyclers in low-regulation countries.[135] EU policy can promote a level playing field by requiring all recyclers of Europe's e-waste to meet minimum treatment standards[136]. This would prevent low-quality treatment, which currently results in loss of valuable materials and environmental harm[137].

125 Allwood et al.,2012, pp. 354 | For instance, alternatives to pulping during recycling can reduce down-cycling.
126 According to Material Economics (insert reference), down-cycling to cast aluminium would no longer be viable in the automotive sector given the impending shift to electric vehicles.
127 Allwood et al.,2012, p.112 | Aluminium, steel and copper could reach 90% cycling rates if processes for re moving trace contaminants are developed.
128 Allwood et al.,2012, p.111
129 For instance, most aluminium foil goes unrecycled but either it is not collected or recycled in mixed streams.
130 Allwood et al.,2012 | Furthermore, economisation of energy, costs and emissions can be achieved by avoiding re-melting in metals production. Re-melting recycled scrap can possibly be avoided in many ways. For instance, either scrap material streams can be put back into circulation without melting or co-locating and coordinating recycling equipment with primary liquid metal processes.
131 Accenture, 2017, p.8
132 Baldé et al., 2017. | The Global e-Waste Monitor estimates the world's e-waste (not including vehicles) in 2016 alone of 44.7 metric tonnes to have contained €55 billion worth of precious metals and other high value materials.
133 Prosumproject, 2018
134 CWIT, 2015
135 Umicore, one of the world leaders in recycling of precious metals, was ranked as the most sustainable company in the Global 100 Most Sustainable Corporations in the World index in 2013.
136 The EN 50625 series of standards for WEEE recycling reflects the state-of-the-art in recycling covering the whole value chain, as well as environment, health, governance and process efficiency provision
137 Example: Ottaviani, J., 2018

There is also a large potential in recovering, recycling and reusing materials like concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil from the over 800 million tonnes of construction and demolition waste generated in the EU each year.[138] Construction and demolition waste, the heaviest and most voluminous of waste streams in the EU, accounts for approximately 25% - 30% of all waste generated in the EU[139]. Enhanced and smarter recycling targets for construction and demolition waste (see sections 5.6 and 5.7), would allow for recovery and recycling of a significant amount of materials across various sectors.

While there is scope for (much) higher levels of circularity in relation to products of the EIIs, there exist important regulatory barriers in achieving higher levels of circularity and materials efficiency. This will be further considered in section 5.7.

4.6. SYNERGIES BETWEEN THE EU'S ENERGY TRANSITION AND THE EIIS' LOW-CO_2 TRANSITION

As shown in the low-CO_2 technology analysis before, future demand for electricity can rise significantly if higher levels of electrification, use of H_2, valorisation of CO_2 and capturing of CO_2 are deployed across the EIIs. To be consistent with the economy-wide carbon neutrality objective this electricity will have to be generated without emitting CO_2 emissions. This additional demand will increase the challenge of greening current power demand progressively, which will necessitate replacing existing generation and providing solutions for increased renewables content which is bringing more and more variability in supply.

The EIIs can assist in enabling the EU's energy transition. Ideally a virtuous cycle is established between the transition of the EIIs and the overall energy transition of the EU. The main goal should be access to competitively priced, abundant and reliable low-CO_2 electricity on the one hand and identification of new or enhanced roles the EIIs can play in facilitating the energy transition on the other hand.

Reducing indirect emissions

In terms of indirect emissions (in particular for sectors with an important share of indirect emissions related to the use of electricity) a 2050 decarbonised European power system would have a major impact in reducing all sectors' CO_2 footprint[140]. EIIs can play an active role in this transition (see points below).

Industrial Low-CO_2 Power Purchase Agreements (PPAs)

Corporate PPAs can be a win-win. They provide financial certainty for utilities and developers (through a stable revenue stream) as well as to consumers. Indeed, long terms PPAs have been part of the industry's strategy for decades as both investors and financial institutions alike seek to diversify market-/price- risk long term (e.g. 20 years). Electro- intensive industries such as the non-ferrous metals industries and chlorine sector are baseload consumers, with predictable uptake in electricity.

138 Deloitte, 2017
139 European Commission, 2018a
140 Eurometaux (Sector Data). | Example: the German non-ferrous metals industry's CO_2 emissions would be reduced by 75% if fully decarbonised electricity is made available and competitive, and challenges are overcome.

This is opposed to the more variable wind energy production profile. However, this obstacle can be overcome, and increasingly, we are witnessing the growth of PPAs with a more variable source - wind energy - in the Nordic electricity market[141].

Financial certainty for utilities brings down the cost of capital and thereby the price of electricity generated. The impact of the weighted average cost of capital (WACC) on the levelised cost of electricity (LCOE) for renewable energy is important, for instance reducing the WACC from 10% to 5% would reduce the LCOE of offshore wind by 30%[142]. In particular, utility scale projects will benefit from this instrument and PPAs will as such assist in bringing additional renewable capacity online.

On the other hand, PPAs enable large energy consumers to secure a supply of green electricity at a competitive price, with long-term price visibility.

Industrial Demand Response

A future power generation system will depend on variable sources and hence will benefit from programmable variation in demand. EIIs, especially when moving to higher levels of electrification, can provide an important service here. Some energy intensive companies and sectors are already active in this area[143]. These projects help deal with the fluctuation in RES. If all EIIs together would on average be able to programme variation in demand by 5- 10%, this would equal a virtual power generation capacity of 3.3-6.6 GWe in the EU[144]. 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 2/3rds of the electricity bill is fixed (tax & network). Price flexibility should be set by the market. Demand-response is not straightforward especially when looking at some of the EIIs 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.[145]

Further R&D in this area will help EIIs deal with finding the optimal balance between reduction of power consumption and productivity.

141 For more details on Renewables and PPAs in Europe see Eurometaux, 2017
142 Hundleby, /g., 2016
143 Djukanovic, G., 2017 | German primary aluminium producer Trimet's trials of the EnPot technology indicate that by being able to dynamically increase or decrease it energy use by 25%, Trimet's goal is to use its smelters to give Germany a virtual battery capacity of 12GWh, which would be approximately 25% of Germany's current pump hydro storage capacity..
144 Eurostat, 2018a | 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).
145 CEFIC *(Sector Data)*, incl. members survey

Storage

With higher production and use of H_2 in the future, EIIs could start playing a role in energy storage. H_2 surplus can be stored and turned into electricity or fuels (role of liquid fuels as long-term storage) if there is market demand for it. Ammonia can become an important energy (or H_2) carrier and can be used for electricity production when needed. The main advantage is that ammonia is a much cheaper and safer way to transport and store energy than H_2.

As mentioned before, EIIs' products will also play a growing role in the development of power storage technologies. The chemicals and non-ferrous industries are critical for the development of batteries. New concrete technologies will allow the large thermal mass of concrete in buildings to be used for energy storage[146].

New value chains for a low-carbon Europe

The production of renewable energy in Europe has created new value chains which significantly depend on materials produced by the EIIs (e.g. steel, silicon, non-ferrous metals, cement/concrete, glass (solar and fibre), chlorine and polymers). The chemical and non- ferrous metals industries will also play a major enabling role in the value chains for the development of batteries (e.g. for electric vehicles and/or grid storage). Further deployment of renewable energy sources and energy storage in Europe could create sustained and significant demand for some of these basic materials. For instance, adding 600 GW of offshore wind capacity (generating approximately 2,600 TWh/pa) to the EU's power generation would lead to a demand of around 108 million tonnes of steel[147], but also generate major demand for cement (foundations or floating platforms), non-ferrous metals (turbine), glass (fibre for blades) and a wide range of chemical products.

The virtuous cycle

A smart design of EU renewables and industrial policies could create a virtuous cycle where long-term contracts with utility scale renewables reduce the cost of investments and hence promote further investments in renewables. Industrial sectors can facilitate the challenges that come with more variable sources of electricity. The materials for these investments will come from basic materials industries, driving demand in Europe for important new value chains.

4.7. EMERGING BUSINESS MODELS

The transition to a low-carbon society, a circular economy and higher levels of digitisation will, under the right conditions, enable new business models or structures. These new business models or structures can potentially further strengthen existing value chains by filling in existing business gaps (see examples below), deepening integration with customer value chains, creating new and dynamic links leading to entirely new value chains, and fostering innovation and employment generation.

146 Cracea, R., 2016
147 Doing Energy, 2013 | Assuming 180 t steel/MW installed offshore wind capacity.
Wind Europe, 2017 | 2,600 TWh offshore wind electricity would represent a significant share of possible future additional ele ctricity demand by energy intensive industries. It also represents around 45% of the economically attractive resource potential (by 2030) in the EU.

Innovation is intrinsic to new business models. New (unique) value propositions emerge through innovation but also as a way to increase economic resilience. In the industrial sector, nine types of business models have been identified[148]. These are *industrial symbiosis* (e.g. valorisation of waste heat and materials waste streams - see section 4.4), *Product Management Service, Cradle to Cradle* (C2C), *Green Supply Chain Management* (GSCM), *Circular Supplies business model, Product Life Extension, Lean manufacturing, Closed loop production*, and *Take Back Management* (TBM).

The product management service business model is underpinned on long-term engagement between a company, a supplier and a customer wherein the company provides customers with a service rather than selling chemical products. The fee-based service (charged as use of chemicals per m^2 instead of product package sold) of delivery, use and collection is based on a closed-loop system. This model is being used in the chemicals industry (see section 4.5) for some specialised chemical products (e.g. chemicals leasing) but could also eventually be applied to products from other industries.

The C2C business model is based on a waste-free bio-based circular economy approach[149]. Green Supply Chain Management is a business model that focuses on greening the supply chain (upstream flow) where raw materials and components are sourced as sustainably and toxic content are either minimised or eliminated. Beyond green purchasing, the business model extends the obligation of environmentally sustainable behaviour to manufacturing/materials management, distribution / marketing and reverse logistics. The Circular Supplies business model is based on supplying fully renewable, recyclable, or biodegradable resource inputs while cutting waste, and removing inefficiencies[150].

The Product Life Extension business model seeks to extend product lifecycle by repairing, upgrading and reselling. Product life extension represents, therefore, an increase in the utilisation period of products. The process is implemented through a dual perspective and requires strategic management preparedness. Longer lasting product feasibility is not only about changing the product characteristics, but also the consumer behaviour needs to be changed through the product design. Lean manufacturing is a business model developed by Japanese companies in the 80s and 90s that focuses on eliminating waste and in the process reducing time and generating more value by using fewer resources. It is widely used in the ferro-alloys & silicon sector.

Closed loop production is a business model in which post-consumer waste is collected, recycled, and used to make new products. This model would align well with the problem of recycling electronic waste[151], dubbed 'urban mining' in Europe (see section 4.5), aiding to recover precious resources which sectors like the non-ferrous metals sector import from outside the EU.

148 ENTRUST, 2016
149 Cradle to Cradle Products Innovation Institute, 2013, p. 53 | Dutch company The Synbra Group's invention - Biofoam, is an example of a cradle-to-cradle alternative to expanded polystyrene.
150 DSM, n.d. | An example is Dutch company Royal DSM's initiative of a cellulosic bio-ethanol (in which agricultural residue like baled corn cobs, husks, leaves and stalks are converted into renewable fuel) which not only created a new source of revenue for DSM, but also helped reduce emissions, produce jobs and strengthen national energy security http://www.dsm.com/corporate/about/business- entities/dsm-biobased-productsandservices.html
151 From scrap vehicles, spent batteries, waste electronic and electrical equipment, and mining wastes.

The Take Back Management (TBM) business model relates to the Extended Producer Responsibility mechanism wherein the producers take responsibility of waste management at end-of-life of the product. This can be a service related to the application or use of the basic materials or services related to circulating the basic materials at the end of their life back to producers.

Value chain integration can take different forms. Companies can move down the value chain and also start producing semi-finished goods next to the basic materials. This would allow for materials efficiency savings (e.g. losses in production) but also the possibility to capture more of the value added generated downstream. Vertical integration can become important in parts of the construction industry e.g. further integration of cement with concrete production or re-use of CO_2 from refineries for Enhanced Oil Recovery (EOR) in the extraction of crude oil. Integration can also happen horizontally where basic manufacturing sectors start to deliver services as an add on to the products delivered. These services can for instance relate to the efficient use of the basic materials supplied or involve reverse logistics to enhance circularity of basic materials and process end of life products and materials.

The above represents a non-exhaustive list. Other examples of new business models can be expected, for example, in new areas such as Demand Response and Storage (see section 4.6) in industry[152].

These new and emerging business models, hold the potential to generate higher levels employment. However, skills development will be a particularly important challenge. The transformation that the EIIs are and will be going through will necessitate a highly skilled workforce "notably linked to digitisation, decarbonisation, innovation, internationalisation and resilience"[153]. Engineers, specialists and business professionals will be in particular demand[154]. There is a widely recognized mismatch and gap, as concerns skills, faced by the EII[155]. The EU's 'New Skills Agenda for Europe' initiative encompasses a 'Blueprint for Sectoral Cooperation on Skills' which can be a good basis to address skills development between the EI and the EU.

152 FTI Consulting, 2016
153 Council of the European Union, 2017
154 CEFIC, 2011
155 Council of the European Union, 2017

KEY MESSAGES

FRAMEWORK CONDITIONS

- Most EIIs operate in highly competitive and dynamic international context. Continued protection of competitiveness is essential to ensure high levels of investment in the EU.
- While EIIs have been working on solutions towards the deep reduction of greenhouse gas emissions, there are also essential framework conditions that will need to be met before adequate progress can be achieved in time.
- Important R&D steps need to be taken. Most promising low-CO_2 technologies will need to prove industrial scale demonstration by 2030 at the latest. Many are still at pilot stage or earlier. Adequate innovation support is required to bridge these innovation valleys of death. Future R&D missions will have to focus on achieving CAPEX and OPEX cost reductions in key enabling low-CO_2 processes.
- The deployment of low-CO_2 technologies will see a much higher demand of electricity from EIIs. This new electricity supply will have to be low-CO_2, ample and competitively priced. A strategic approach that links the EU's energy transition with the transition of EIIs is needed. This includes ensuring that (increasing) regulatory costs do not deter investments in new technologies and that long term contracts (in particular renewable PPAs) are encouraged and facilitated.
- The necessary infrastructure for H_2 and CCU/CCS in Europe is not or not adequately present. Urgent efforts need to made to map infrastructure needs and develop European industrial projects of common interest.
- The CAPEX for industrial low-CO_2 transition will be very high and significantly above current investment levels of EIIs and investment decisions in low-CO_2 processes will not happen if OPEX is not competitive.
- Addressing the CAPEX-OPEX challenge will require a mix of instruments with the goal to increase industrial investment levels *well above* their current rate *in the EU.*
- New low-CO_2 process plants will likely be constructed at same industrial sites and some existing installations (which are likely already written off) will have to be replaced, leading to additional costs (CAPEX+OPEX) for producers. Allowing accelerated depreciation of new installations and other tax incentives can help address this.
- European environmental state aid guidance will have to be reviewed to allow Member States apply one or more of the above mentioned support instruments.
- The urgency of all of the above mentioned facilitating conditions to emerge is high. Long EIIs investment cycles imply that the next investment will have to be compatible with a 2050 framework.
- The above mentioned elements can inform the development of a new EU industrial strategy for EIIs and their value chains as part of a competitive low-CO_2 transition.

5. FRAMEWORK CONDITIONS

5.1. INTRODUCTION

Starting from main elements presented in the previous chapter this chapter looks at the key enabling conditions towards the solutions mentioned, and which existing or new barriers need to be overcome. The key framework conditions fall into 6 categories: R&D challenges, securing adequate and competitively priced low-CO_2 electricity supply, infrastructure needs, financing challenges, conditions for enhanced circularity and materials efficiency, and regulatory challenges.

Next to the framework conditions that can enable deep emission reductions in EIIs there are two main horizontal constraints that impact all other factors.

The first horizontal constraint is that the industrial transition will have to happen in highly competitive and dynamic international environment. Many products by EIIs have a high trade intensity and are exposed to a high degree of international competition. Furthermore, as part of these global markets, investments decisions in new production capacity (sometimes replacing existing capacities elsewhere) can happen anywhere in the world and these link strongly to regional investment climates and market potential. The risk of an unlevelled playing field for investments in Europe vis à vis the rest of the world, in particular due to higher regulatory, energy, raw materials costs, does continue to exist. Furthermore, some sectors face unfair international competition e.g. due to dumping. EIIs in Europe, due to their deep value chains in the real economy have shown significant vulnerability to global economic disruptive events. As shown in chapter 3, most EIIs (except chemicals) have production levels still below pre-2008 economic crisis levels. The transition of EIIs to a low- CO_2 economy will be a high risk operation, even if most framework conditions are fulfilled. It is therefore essential that this process is accompanied with EU protection of EIIs from unfair trade practices, carbon leakage and other factors that can harm the international competitiveness of companies. As will be shown in section 5.5 the challenge is not only to avoid investment leakage out of the EU for EIIs, but to increase the current level of investments towards the deployment of low-CO_2 technologies.

Without a healthy industrial base in Europe there will be little scope for the development and deployment of low-CO_2 technologies in the EU.

The second horizontal constraint is time (and timing). The industrial structure of EIIs generally shows strong economies of scale and high capital intensity. The processes involve high fixed costs and have potential for significant energy efficiency and economies of scale, which results in large scale processing plants that require high upfront costs. These costs need to be earned back in cyclical markets (with large variations in prices and profit margins), resulting in uncertainty and long payback times and investment cycles. Investment cycles for major reinvestments can typically range between 20-40 years[156]. This implies that for most energy intensive companies, 2050 is just one (large) investment cycle away from today.

156 Wesseling, J.H. et al, 2017

At the same time most if not all of the necessary conditions (such as construction of demonstration plants, addressing technology costs, energy costs, infrastructure and financing) to make large low-CO_2-process investments are not in place (see next sections). These critical conditions will have to be continuously addressed within 10 years at the latest together with major strides in investment in necessary infrastructure. As such these elements can be seen as the outline of an industrial policy in support of significant emission reductions in EIIs.

5.2. R&D CHALLENGES

Following the assessment of low-CO_2 technologies under development, three main future R&D challenges emerge:

- The need to scale up breakthrough technologies towards demonstration and commercialisation.
- Optimal combination and integration of technologies (incl. breakthrough technologies)
- An increased focus on cost reduction.

Most of the technologies assessed in this contribution hover at TRLs between 5-7, while a sizeable amount others still have to reach TRL 5 (see addendum). Designing and building a pilot or demonstration plant at scale forms indeed one of the biggest challenges for most of the low-CO_2 options on the horizon. The main reason for this is the large capital requirements together with the still high technology risks related to this part of the R&D phase. The combination of both elements make it highly unlikely that the private sector will engage in this on its own. Bridging this so-called valley of death will require significant financing support[157], including the willingness of the public sector to participate in the risk taking of this process. For CCU and new bio-based products new large scale projects are also needed to facilitate the market entrance of new CO_2-based products, since risk-sharing at demonstration phase is critical to enable test and approval phases by value chain partners. Companies down the value chains should be encouraged to test CO_2-based and bio-based products. Support for OPEX and CAPEX of projects up to first production is therefore essential for market entrance.

While some supporting technologies are advancing well on their own the integration of these into a full production system remains a challenge still. Examples are the production of H_2, the transformation of biomass to fuels and technologies to capture CO_2 that will require integration into e.g. ammonia, steel, high value added chemicals, and complete CCU and CCS systems.

Even if the low-CO_2 technologies reach maturity, their market uptake will depend on the operational costs. This will have to become one of the main areas for further R&D. Cost optimisation can be achieved by having multiple technologies reach full scale size to allow for experimentations with design improvements on an industrial scale. Other focus areas for mission oriented R&D to lower production costs for low-CO_2 processes include[158]:

157 Eurofer (Sector Data) | For example, the total cost of getting all steel sector low-CO_2 R&D projects up to industrial scale will be around EUR10 Bn.

158 Dechema, 2017, p.143-147 | A rich and promising field of research is related to the development of new (and low-cost) catalysts that likely will play an important role in bringing down cost (e.g. through increased yield or by lowering energy needs) for some of the mentioned technological options, in particular related to electrochemistry.

- Reducing the cost of low-CO_2 H_2 production (e.g. for electrolysers CAPEX <EUR600/kW installed capacity and OPEX (electricity) < 3-4 kWh/Nm^3 H_2) and development of alternative production of low-carbon H_2 such as methane pyrolysis and water photolysis;
- Reducing the cost of biomass (waste) transformation to fuels or basic chemicals (e.g. bio-ethanol < EUR 300-350/t[159])
- Optimisation of technologies needed for the electrification of high temperature furnaces (comparable to commercial sizes of current glass, cement and ceramic furnaces) and other electricity based processes (including electrochemistry, intensified processes with alternative energy forms such as plasma and microwave technologies, and pyrolysis technologies) at industrial scale.
- Reducing cost of capturing and purifying CO_2.

Tackling these three elements (scaling, combination and cost reduction) will require the realisation of a large and ambitious mission oriented R&I program to further investigate and activate the potential of these new technologies. Further R&D support from public sources will be essential. This includes the use of Public-Private-Partnerships (PPPs) to focus R&D efforts and to enable risk sharing for investments for demonstration of innovative technologies. Finance to enable the fast realisation of demonstration plants at industrial scales is an important prerequisite. By 2030 the most promising technological options should have been thoroughly demonstrated at industrial scale.

5.3. SECURING SUFFICIENT, RELIABLE AND COMPETITIVELY PRICED LOW-CO_2 ELECTRICITY

While it is clear that higher levels of electrification in EIIs and new low-CO_2 processes (e.g. processes based on H_2 from water electrolysis, some CCU, recycling technologies, and CCS) will require significant amounts of electricity to operate, it is by no means certain that sufficient, reliable and competitively priced[160] (and non-volatile) low-CO_2 electricity will be available to enable this transition. This will therefore be one of the most important framework conditions for the transition to a low-CO_2 industry in Europe.

Final electricity consumption by EIIs in 2016 was 581 TWh. It represented 57% of overall industrial electricity consumption (1,010 TWh) and 20% of economy-wide final electricity consumption in the EU (2,784 TWh)[161]. Recent work by Eurelectric[162] considered future electrification rates and final consumption of electricity by EU industry under 2050 GHG reduction scenarios for the EU (i.e. -80%, -90% and -95% emissions compared to 1990).

159 Jernberg, J., et al., 2015 | At bio-ethanol production prices below 300-350 EUR/t building an ethanol dehydration plant for production of ethylene would be investment grade (payback time < 2y)
160 i.e. competitive electricity price that allows low-CO_2 technologies to compete with conventional technologies on an international market.
161 Eurostat, 2018a
162 Eurelectric, 2018

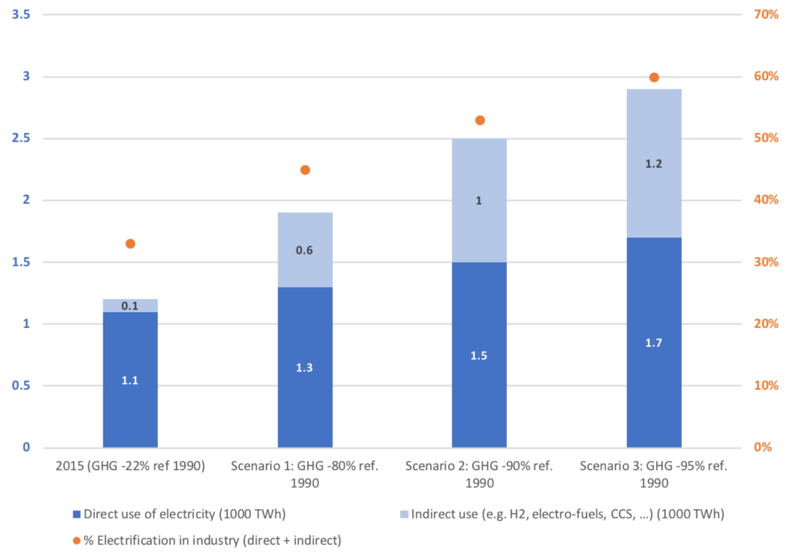

Figure 14: Electricity demand (1,000 TWh) and level of electrification in EU industry under -80%, -90% and 95% greenhouse gas reductions by 2050 (ref. 1990) (Source: Eurelectric 2018)

These scenarios show a clear trend towards higher electrification (up to 60% in -95% scenario) of energy use in industry and a significant rise in demand, in particular demand through H_2 use as a feedstock, CCS and production of fuels using electricity. Final demand by industry could reach almost the same level as the current EU economy-wide final demand for electricity. It would also represent 50% (3,000 out of 6,000 TWh) of final EU electricity consumption in 2050 (under a -95% scenario), making industry with distance the largest final electricity consumer in the EU. While this trend is in line with the observations in chapter 4 it might be even be underestimating future electricity demand and electrification rates in industrial sectors. An aggregation (for illustrative purposes) of a selection of low- CO_2 pathways and technology studies by industries[163] and other sources (see figure 15) shows a potential future electricity demand from 2,980 to 4,430 TWh for EIIs alone.

163 Based on various scenarios developed by energy intensive industries.

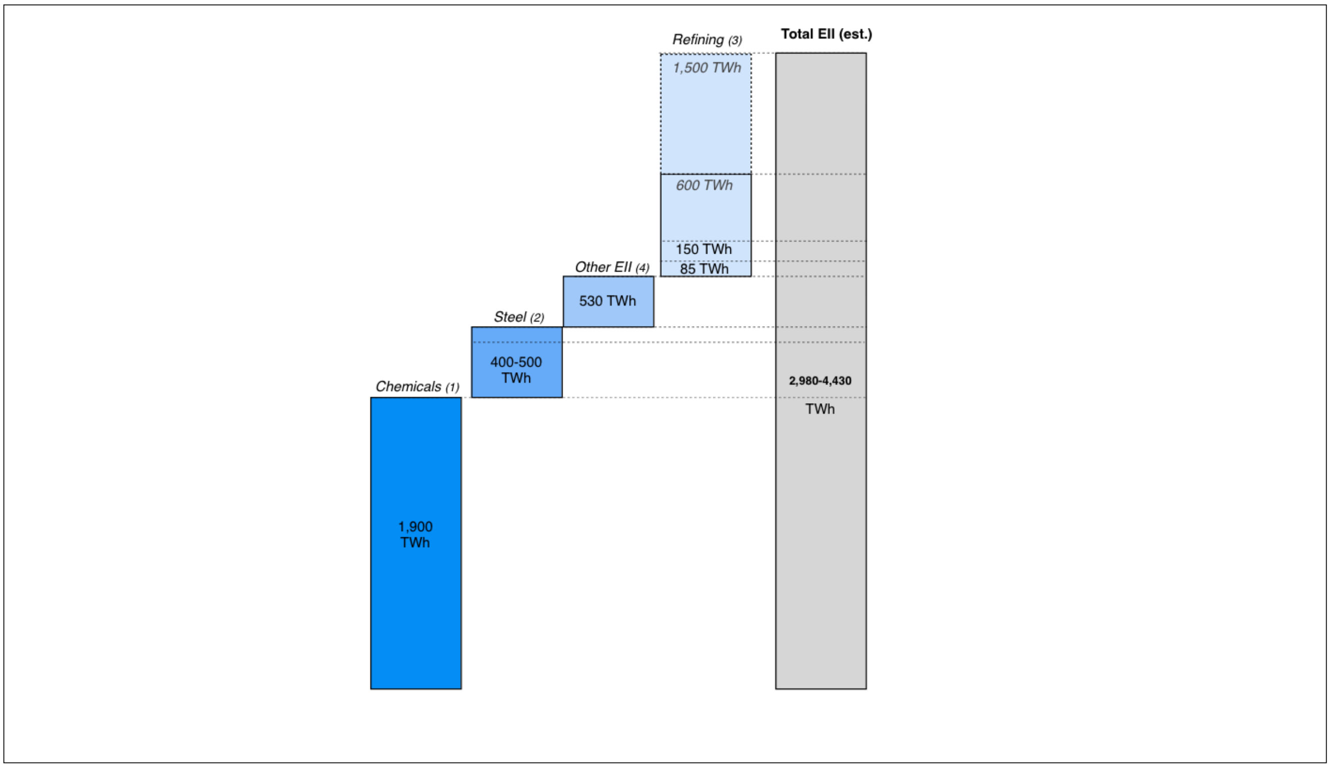

Figure 15: Aggregation of possible electricity demand (TWh) from energy intensive industries using information from low- CO_2 pathways and other sources[164]

However, high levels of electrification (incl. use of H_2 as feedstock) will only happen on a large scale in Europe if electricity prices (for low-CO_2 electricity) for EIIs become very competitive and supply is adequate.

Figure 16 shows average electricity prices for some energy- and electricity intensive sectors in the EU (source CEPS, 2012). Estimates by the IEA[165] show that (renewable) electricity prices for industry will have to be below the lowest current average price (e.g. around EUR 25/MWh) for H_2 based ammonia production, H_2 based steel production and CCU/H_2 based methanol production to remain competitive in global markets or compared to current production costs. Dechema[166] mentions low-carbon ammonia production costs of EUR 255- 590/t NH_3 at electricity prices of EUR 10-30/MWh compared to natural gas based ammonia production cost of around EUR 350/t NH_3.

164 (1) Dechema, 2017 | *ambitious 2050 scenario* (covers only production of ammonia, olefins (incl. BTX), methanol and electricity based steam generation and recompression). The quantitative analysis is based on existing technologies, and scenario development up to 2050 do not take into account the development of next generations or breakthrough technologies.
(2) Eurofer, 2018
(3) FuelsEurope *(Sector Data - Concawe on-going work)* (2018) | Preliminary estimated for 2050: ≈ 85 TWh electricity demand after the implementationof CO_2 efficiency measures (Stage 1). When different low-carbon feedstocks are considered, the electricity demand would increase from 5 times (Bio-feedstock pathways) up to 20/50 times for combined pathways (bio-feedstock uptake + power to liquid production) vs the estimated 2030 reference case (Reference 2030: 30 TWh). 2030 reference demand scenario: Scenario assuming similar complexity in the sites and no changes in total demand ratio of refining products. Energy efficiency measures continuing the historical rate of improvement.
(4) Eurostat, 2018a and Cembureau (Sector Data) | Estimate: 2016 electricity consumption of other sectors (i.e. non-ferrous, non-metallic minerals, pulp and paper) [248 TWh] + 60% electrification of solid fuel/gas/oil/derived heat in 2016 [270 TWh] + additional e lectricity demand for CCS in cement [+/- 12 TWh]

165 OECD/IEA, 2017

166 Decehma, 2017, p. 59

Further electrification of heat can happen at less stringent conditions (due to efficiency gains and other co-benefits) but the price gap between natural gas and electricity in Europe is still wide and will need to be bridged by significant efficiency gains through electrification. As stated before, high temperature furnaces using electricity (e.g. microwave based) have not yet reached commercial scale.

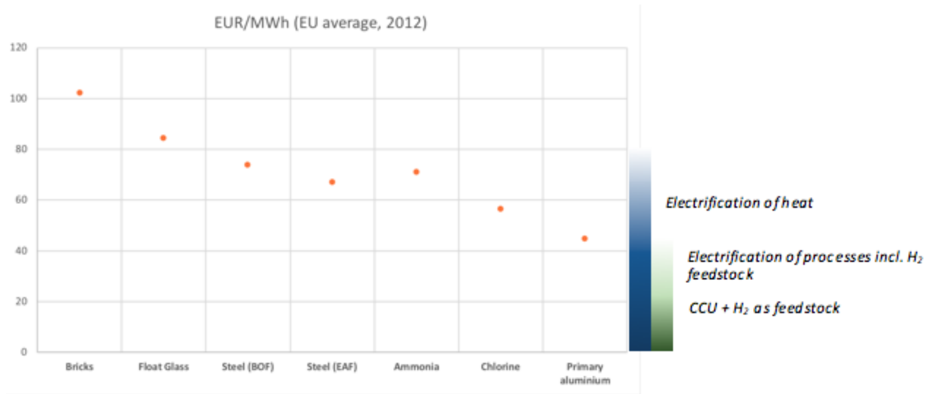

Figure 16: (Left) Average electricity prices for selection of energy/electro intensive producers (Source: CEPS) and (right) indicative price ranges where types of electrified industrial heat and processes could be able to compete with existing processes[167]

Furthermore, the supply of this (low-cost) renewable electricity to power industrial processes will need to be adequate (i.e. being able to meet demand and ratchet up supply in line with above mentioned scenarios) and have a low-price volatility.

The fact that industry will likely become the largest electricity consumer under 2050 scenarios together with the stringent requirements on price and adequacy will make the fulfilment of final electricity demand with renewable energy by 2050 much more strategic beyond planning for total final demand in the EU by 2050. Europe's energy transition cannot be seen separate from industrial transition and vice versa. From an economic and strategic perspective, it is therefore important to think about a "merit order" of demand for each new segment of supply of renewable electricity, i.e. as a new quantity becomes available, which is the most cost-effective (asset conversion costs) and carbon effective (most GHG emission avoided) for use of this electricity.

Current policies might stand in the way of higher electrification (including use of H_2) in EIIs. The indirect costs under the EU ETS are or can become a serious deterrent towards investments in (new) processes that require high amounts of electricity.

Further efforts must be made to lower regulatory costs related to electricity consumption by EIIs on a level playing field basis across the EU and also vis-à-vis international competitors.

167 OECD/IEA, 2017 | Electrification of heat can imply important efficiency gains and other economic benefits for producers. Aver age end- use efficiency gain in moving from natural gas based heating to electrified heating is estimated to be factor 2.35 (ranges from 1-8) based on dozens of case studies (Source: European Copper Institute & Leonardo Energy, 2018, electrification as decarbonisation rout e for industry) and could in some cases where energy savings are very large become possible at prices comparable to current EU average electricity prices. Ammonia production using hydrogen would become competitive at 25 EUR/MWh (and high -above 3000h/pa- utilization factor of electrolysers). Hydrogen based steel production will require lower prices and electrolyser efficiency of 3KWh/Nm^3 H_2) to be competitive with steel BF-BOF route. Methanol production using CO_2 and hydrogen would require similar electricity prices, but utilization of carbon monoxide (CO) and hydrogen would be easier (and hence a bit less stringent with regard to electricity prices) to ac hieve competitive product prices.

A more adequate compensation system for the indirect costs of the EU ETS is needed.Indeed, compensation for the indirect costs of the EU ETS is partial, voluntary and declining, which acts as a major disincentive to further electrification.

Allowing EIIs across the board to sign long-term electricity contracts, in particular through renewable PPAs, will help address risks related to price volatility (and as stated before, reduce the cost of capital for utility scale renewables projects in the EU). However, do to the marginal pricing mechanism, even when industries sign long term PPAs with renewable providers, they are still subject to indirect carbon costs (even though the electricity purchased does not contain carbon).

Finally, there is also a risk that the development and deployment of low-CO_2 technologies in EIIs will conflict with provisions in the EU's energy efficiency directive. As mentioned before, electricity, and in some cases over-all energy demand, might go up due to the application of low-CO_2 technologies, while the energy efficiency directive strives towards the reduction or savings of energy.

5.4. INFRASTRUCTURE NEEDS

Some of the main technologies that can reduce GHG emissions in EIIs will require the timely development and financing of adequate infrastructure. In particular CCS (and to a lesser extent CCU) and processes using low-CO_2 H_2 will require reliable transport and storage infrastructure. Furthermore, higher levels of electrification might need strengthening of high voltage networks close to industrial consumers. Finally, supply and logistics chains for enhanced use of biomass resources will also need to be developed.

Currently, most of this infrastructure is not in place across the EU. There is around 1,600 km of H_2 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[168] and there is only limited transport of ammonia via pipelines.

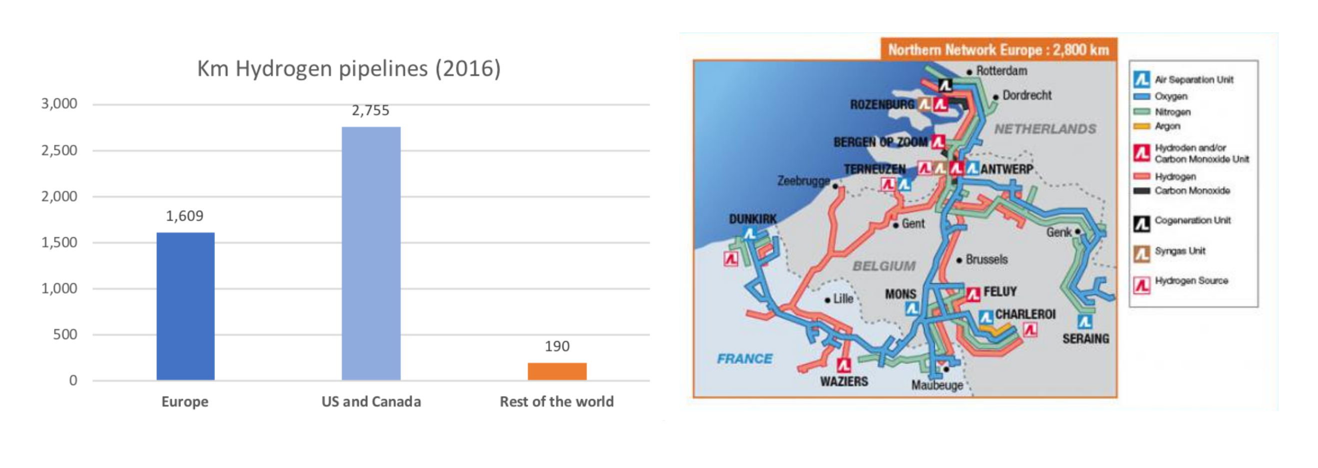

Figure 17: (left) Kilometers of H2 pipelines in EU vs US/Canada and rest of the world (2016 data, Source: H2tools, Pacific Northwest National Laboratory) (right) out of 1,600 km H2n pipelines in Europe 850 km can be found in Belgium and Netherlands. (390 km in Germany and 303 km in France) (source picture: Hydrogen Europe/Air Liquide)

168 Portstrategy, 2017 |The Port of Rotterdam Authority is exploring opportunities with Nederlandse Gasunie (Gasunie) and Energie Beheer Nederland (EBN) to achieve a basic infrastructure to capture and transport carbon dioxide (CO_2) in the Port of Rotterdam area.

The current (or planned) olefins networks in Europe (see figure 19) could be taken as a proxy for the network size and capacities needed in a future low-CO_2 European industry. Developing such networks will require a significant amount of capital and time (e.g. planning, permitting and getting public acceptance).

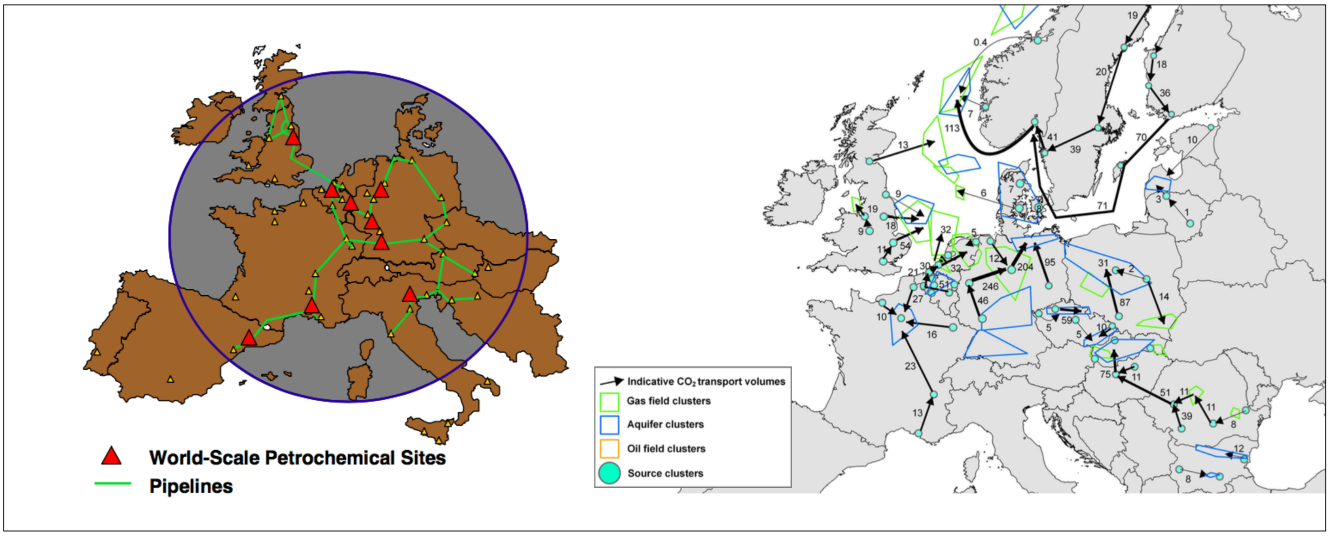

Figure 18: (Left) Proposed interconnected EU olefins network (Source: APPA/Petrochemicals Europe), (Right) Map of large-scale CO_2 transport infrastructure for 2050. Arrow represent the major transport corridors; the numbers indicate the transported volumes in Mt/yr. Blue circles represent clusters of capture installations, polygons represent clusters of storage sites: saline formations (blue), gas fields (green). Oil fields are not shown on this map. In this scenario, both onshore and offshore storage is assumed possible. (source: CO_2 Europipe, 2011)

There is therefore an urgent need to strategically map the infrastructure needs in relation to an industrial low-carbon transition[169]. A bottom up approach to identify these needs could be the way forward. This could imply starting the mapping from the possible technology choices and synergies at local or regional industrial clusters. These can look at advantages of scale through shared infrastructure for multiple (large) industrial installations and sectors in the same region. Secondly, mapping should take into account existing connections between industrial clusters across borders (e.g. existing pipeline infrastructure connection regions) and how economic or other synergies between regions can be realised. These different regions will have to coordinate their approaches as to avoid possible incompatibilities in supply chains (e.g. structural imbalances between supply and demand for H_2 and/or CO_2). Finally, the risk of industrial clusters becoming isolated of new low-CO_2 infrastructure must be identified together with options to mitigate this. This mapping exercise will give better insights into the capital needed for low-CO_2 infrastructure but also indicate the priority areas and (need for) interconnections.

A new EU platform consisting of industrial actors, research and technology organisations (RTOs), technology and infrastructure providers should be established to map necessary future EU (cross-border) infrastructure for EIIs. This platform shall by 2025 propose a first list of European industrial projects of common interest related to infrastructure for further development and financing. No single company or sector will be able to provide the capital for these infrastructure investments on their own, hence instruments will have to be developed to assist with enabling the finance.

169 Dechema, 2017 | This can include also the development of a central European database of CO_2 sources and infrastructures that would provide potential for industrial symbiosis, including e.g. emitters below the threshold for reporting to the European Pollutant Release and Transfer Register

5.5. CAPEX AND OPEX CHALLENGES IN AN INTERNATIONAL COMPETITIVE ENVIRONMENT

Industrial roadmaps and pathways developed in recent years give some insights into the CAPEX and OPEX needs for industrial low-CO_2 transformation, assuming all conditions in the studies are met. Table 7 below gives an overview of additional CAPEX for a selection of low- carbon roadmaps or pathways for industrial sectors (at EU and national levels). Currently there is no estimate of aggregate additional CAPEX needs across EIIs in the EU towards 2050 reduction pathways. The CAPEX required (at EU level) is likely, in all sectors mentioned, well above their current investment levels in the EU[170].

Source	Scope *Region (timeframe)*	*Sector*	Scenario	Mitigation potential	CAPEX (EUR Bn)
Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050[171]	UK (2012-2050)	Iron & Steel	Max tech	-60%	0.8
		Chemicals	Max tech	-88%	5.6
		Oil Refining	Max tech	-64%	0.7
		Pulp & Paper	Max tech (electrification & clustering)	-97.5%	1.4
			Max tech II (biomass)	-98%	1.4
		Cement	Max tech (with CCS)	-62%	0.8
		Glass	Max tech (with CCS/U)	-92%	0.2
		Ceramics	Max tech	-60%	1
		All[172]	Max tech	-73%	22.5
Roadmap for the Dutch Chemical Industry towards 2050[173]	Netherlands (1990-2050)	Chemicals	2030 compliance at least costs	-95%	16[174]
			Direct action and high-value applications	-95%	27[175]
Energy transition: mission (im)possible for industry? A Dutch example for decarbonization[176]	Netherlands (1990-2050)	All industry	Steeper route	-95%	25
Klimapfade für Deutschland[177]	Germany (1990-2050)	All industry	80% climate path	-80%	120
			95% climate path	-95%	230

170 Dechema, 2017 | The annual CAPEX estimate by Dechema for chemicals (ambitious scenario) is almost 10 times the current investment levels by the European chemicals sector.

171 Iron & Steel BAU: -15%, CAPEX £0.3; chemicals BAU: -31% CAPEX £0.6; oil refining BAU: -44%, CAPEX £0.2; pulp & paper BAU: -32%, CAPEX £0.7; cement BAU: -11.9%, CAPEX £0.3; glass BAU: -36%, CAPEX £0.03; ceramics BAU: -27%, CAPEX £0.3; all industry (incl. food & drink) BAU: -32%, CAPEX £6. All figures provided for current trends scenario. Assumptions for max tech: TRL at pilot sc ale, no cost constraints, deployment rate 'highly ambitious but also reasonably foreseeable', unlimited availability of biomass, CC potential 'highly ambitious but also reasonably foreseeable, electricity grid decarbonisation.

172 All industry mentioned above plus the food and drink industry.

173 Assumptions: availability of biomass and renewable energy, energy efficiency improves 1.0%/year after 2005.

174 ECOFYS & Berenschot, 2013, p. 46 | The CAPEX for investments needed outside the Dutch chemical industry (e.g. CCS on waste incineration, offshore wind and bio-refining) are estimated to be EUR 24.9 Bn.

175 ECOFYS & Berenschot, 2013, p. 46 | In this case CAPEX for investments needed outside the Dutch chemical industry are estimated to be EUR 37 Bn.

176 Mckinsey & Co, 2017, p.35 | Reference scenario: -40% by 2030 with no sig. reduction possible after, CAPEX n.a. Assumptions for the steeper route: shift to renewable electricity, electrification of industry. Mckinsey & Co, Energy transition: mission impossible for industry

177 BCG and Prognos, 2018., p. 165 | Reference scenario: -61%, CAPEX n.a. Assumptions for reference scenario: approx. 50% GDP growth by 2050.

Source	Scope *Region (timeframe)*	*Sector*	Scenario	Mitigation potential	CAPEX (EUR Bn)
The Ceramic Industry Roadmap: Paving the way to 2050 [178]	EU (1990-2050)	Ceramics	Scenario 2	-78%	90 + 40 for writing off plants
Investing in Europe for Industry Transformation: 2050 Roadmap to a low-carbon bio-economy[179]	EU (1990-2050)	Pulp & Paper	Scenario -80%	-80%	24 (transformation existing processes) + 20 (production of new bio- based products)
FuelsEurope[180]	EU (1990-2050)	Refining	Stage 2	-70% + additional savings from low-carbon feedstock	600[181]
Low -carbon energy and feedstock for the European chemical industry[182]	EU (2015-2050)	Chemicals	Ambitious scenario	-84%	672
CEMBUREAU	EU (1990-2050)	Cement	-80% by 2050	-80% includes CCS for 85% of cement production (equivalent to 59% of cement plants)	11.6[183]

Table 7: Overview of additional CAPEX for a selection of low-CO2 roadmaps or pathways for industrial sectors (at EU and national levels)

While the estimated CAPEX needs are already high across all sectors, they only show a partial picture. Capital related to accelerated depreciation of existing installations to be replaced by low-CO_2 technologies is in most cases not been accounted for[184]. Future OPEX is at least as important as the CAPEX since it will determine the competitiveness of future production in the EU. Increase in CAPEX can be significant.

178 Scenario 1: -65%, CAPEX n.a. Assumptions: energy costs 2.5x current rate, costs of biogas 2-3x that of natural gas, rising cost of raw materials from Asia, constant level of production with a similar product mix, barriers regarding alternative fuels are overcome a nd regulators treat syngas and biogas as producing net-zero emissions.

179 Assumptions: value added compared to 2010 to increase by 50%, shift to the circular bioeconomy.

180 For 'stage 1' scenario: -70% with CAPEX €45. (1) The 2050 scenario represents a high uptake scenario where all the measures are incentivized by a lower electricity to natural gas price ratio. The basic assumption for the 2050 horizon is that the maximum level of realistic deployment will be achieved for each identified opportunity at the EU level, assuming no change in the activity level of the sector. (2) The preliminary capex estimate varies depending on the combination of different low carbon feedstock (availability) and technologies considered (different pathways chosen by individual refineries). This capex assumes the co-processing or co-location of new conversion technologies within or close to the refinery, maximizing the synergies and utilization of the existing refining unit. The CAPEX for all investments refers to the generic cost of the different technologies and opportunities identified, excluding investment out of the refining system. The actual cost of implementation could be much higher determined by the specific conditions of each individual asset which may have a significant impact on the final capex required.

181 Based on Concawe's preliminary modelling work (potential future demand) complemented with external references (in terms of costs for alternative low carbon feedstock and their associated conversion technologies).

182 For BAU: +119 $MtCO_2$ (an increase proportional to production volume. Savings from efficiency measures not included), CAPEX €80.5. Assumptions: 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 decarbonisation.

183 Annual CO_2 avoidance cost in 2050 (OPEX): 3.9 billion €/a

184 Cerameunie, paving the way to 2050, the ceramic industry roadmap estimated the CAPEX to be EUR 90 Bn for conversion of 50% of furnaces to electricity and remainder to syngas/biogas with natural gas co-firing. An additional EUR 40 Bn cost estimate relates to writing off plants before the end of their life and lost sales during downtime for plant modifications.
for the ceramics industry in the EU.

A 95% reduction pathway for industry in the Netherlands would see OPEX go up by factor 40 between 2025 and 2050[185]. However, if electricity prices were to fall to average levels of EUR 20/MWh (from EUR 50/MWh today, including transmission and distribution costs), then the entire cost of this Dutch decarbonisation program for industry would be lowered by more than 60%. This demonstrates again the critical framework condition of competitive power prices. The German BDI roadmap study shows more favourable OPEX conditions with major net cost savings through higher levels of energy efficiency in an 80% reduction scenario (ref. 1990) and with energy savings outweighing the increased cost of energy carriers in a 95% reduction scenario[186]. It must be stressed that the scenarios in the BDI study also include important boundary conditions regarding the safeguard of competitiveness of German industry which hence enable investments.

The strategic relationship between OPEX and CAPEX in this context is quite straightforward. High CAPEX investments in new processes with a significantly higher OPEX compared to (international) competitors will likely not happen. There is no business case to be made. Therefore (as stated before) future EU R&D missions will have to focus on enabling low-CO_2 technologies to deliver OPEX that is competitive with conventional production technologies. Furthermore, energy carriers that will become the main vectors for low-CO_2 processes (e.g. electricity and H_2) need to remain competitively priced in Europe for EIIs. In particular, regulatory costs are of concern here. Finally, it will take time for new processes to iron out (first of a kind) issues that hamper process efficiency, leading to (much) higher costs initially. It is therefore important the EU supports the creation of lead markets through public procurement, which will allow innovative producers and processes to gain access to the market. This approach will also apply to new product types (or even business models) with a much lower CO_2 footprint for which there is currently no market. Another instrument that can help with market creation (or prevent loss of market share) is the smart use of standardisation[187].

The low-CO_2 CAPEX-OPEX challenge will require a mix of instruments with the goal to increase industrial investment levels *well above* their current rate in the EU. With this challenge in mind, current initiatives[188] and proposals on sustainable finance are highly insufficient. The question here is not on how to enhance the sustainability of existing financial flows (e.g. labelling and development of taxonomies) but how to significantly *ramp up* investments in low-CO_2 industrial processes. This will likely require additional instruments of the right proportions.

For most EIIs, the current production location has significant strategic value (e.g. connections to infrastructure and logistics, proximity to raw materials supply chains and/or customers). Most investments in low-CO_2 processes will therefore likely happen at the same location. While retrofits of existing process installations towards low-CO_2 processes will likely be prioritised, this will however not always be possible. This implies that major brownfield conversions will have to be part of an industrial low-CO_2 transition. This type of transition will always be more expensive compared to greenfield developments. Existing productive assets will have to be dismantled and sites will have to be prepared for installation of new process facilities.

185 Mckinsey & Co report, 2017 | From EUR 100 million per year in 2025 to EUR 4 billion by 2050.
186 BCG and Prognos, 2018, p. 165
187 e.g. broader standards that allow for use of alternative binders or new concrete formulas in the construction industry.
188 e.g. the recommendations by the High-Level Expert Group on Sustainable Finance

This will pose major economic accounting issues for companies and can make the business case of low-CO_2 projects unviable (even with attractive financing programmes). The EU's and national financing instruments will therefore need to take into account the additional constraints that come into play during the conversion of existing process installations which have been written off. This can include allowing for accelerated depreciation of the new assets (to lower taxation basis) which are being developed, other tax abatements and financial support for preparation of site conversion.

Some of the above mentioned instruments that assist energy intensive industries might not be covered by the current scope of environmental state aid guidance. Therefore, it is recommended that these guidelines be reconsidered and aligned with industrial low-CO_2 transition.

5.6. CONDITIONS FOR ENHANCED CIRCULARITY AND MATERIALS EFFICIENCY

All EIIs are extremely reliant on raw materials and almost all EIIs already depend highly on recycled materials as raw materials input (see section 3.4). Security of raw materials supply (especially critical raw materials) is indispensable for some sectors which rely heavily on raw material imports into the EU like the steel, non-ferrous metals, ferro-alloys and silicon, chemicals and fertilizers sectors. For most basic materials therefore, enhanced circularity will become even more critical over the next decades as a strategy to reduce emissions reduce energy use[189], maintain supply security, and enhance production and growth while reducing costs.

In 2018, the EU adopted an ambitious waste framework directive with binding targets for recycling (55% by 2025 and 65% by 2035 for municipal waste, 65% by 2025 and 70% by 2035 for packaging waste[190]).[191] Mechanisms like Extended Producer Responsibility (EPR) which extends producer responsibility for a product beyond their scope have been pioneered in Europe nearly two decades ago. But there is still a need for more elaborate, ambitious European circular economy regulations with long term trajectories given that around 80% of the goods produced by the EII are traded all over Europe[192]. While Europe is already a success story when it comes to steel, non-ferrous, paper or glass recycling for instance, important challenges remain in other value chains and in particular with regard to maintaining the quality of basic materials in recycled product streams.

European energy intensive industries already recycle and recover significant quantities of waste. In the cement industry, alternative fuel use represents 44% of overall fuel needs and alternative fuels are sourced from a wide variety of waste streams. A structured waste policy is needed which recognises and rewards the benefits of co-processing[193] and its close integration with other industries, ensures a level playing field for the use of biomass waste by removing subsidies that favour one industry over another, recognises co-processing in the waste management hierarchy (between incineration and recycling) as a combination of simultaneous energy recovery and recycling of the minerals, facilitates access to raw materials and enhances the use of waste and by-products. An R&D policy promoting recovery of materials with calorific potential from waste for co-processing will also useful in this regard.

189 Eurometaux (Sector Data) | For example, Aluminium recycling is upto 95% less CO_2 intensive vs primary aluminium making while Copper recycling is upto 80% less CO_2 intensive vs primary.
190 Packaging waste covers plastic, wood, ferrous metals, aluminium, glass and paper and cardboard.
191 European Commission, 2018b
192 Crisp, J., 2017
193 Co-processing refers to the simultaneous recycling of materials and recovery of energy within one single industrial process.

More efforts are needed to improve the sorting and recovery of construction and demolition waste which would allow for recovery and recycling of materials across various sectors. For instance, steel reinforcement bars in sub-surface concrete are not always extracted after demolition[194], or new technologies like concrete smart crushers remain commercially unattractive because of a lack of regulatory necessity to separate demolition waste in the first place.[195]

Because the main customers of EIIs are other industries or businesses, many of the regulatory and other solutions will have to happen downstream. This includes the design for optimal use of basic materials (preventing over-engineering), design for reuse (or in other words, longer lifespan of final products), design for disassembly (i.e. to avoid contamination of basic materials and save costs in disassembly processes that enable reuse and recovery), and improved end of life processes (smart disassembly and demolition processes that allow for higher and less contaminated recovery of basic materials). Improved reverse logistics will also allow to close some material loops[196] and improve economics of recycling. For instance, alloys today are optimised for particular applications and to facilitate lighter designs. There therefore exists large competition amongst metal suppliers in the market. Regulating the number of alloy combinations in use would help reuse and recycle greatly[197]. Such action downstream action would significantly boost secondary production, allowing greater investment in more efficient circular technologies which would enable the closing of loops[198].

194 Allwood et al, 2012, p. 64.
195 Cembureau. 2013 | Currently cement is not being recycled separately although research has been initiated to recycle the fines fractions of concrete. Concrete can be recycled 100% at its end of life. Crushed concrete can be reused as aggregates in new concrete, or alternatively in lower-grade applications such as in road base. The choice of application should be based on the optimum balance of sustainability and long-term technical performance. Using recycled concrete as the aggregate is particularly useful because it often has better compaction and density properties and is generally cheaper than virgin material.
196 This type of closed loop is not always possible, although loops can feed into other value adding processes.
197 Allwood et al, 2012, p. 213
198 Allwood et al, 2012, p. 110

5.7. REGULATORY FRAMEWORK

THE NINE ELEMENTS THAT WOULD ENSURE THAT EIIS SUCCESSFULLY TRANSITION TO A LOW-CO_2 ECONOMY ARE:

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-CO_2 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*
9) *Transparent accounting framework for CCU across sectors and value-chains to allow business cases to emerge*

Throughout this contribution, regulatory barriers and opportunities have been identified which will determine whether EIIs will thrive and invest in the low-carbon transition. The paragraphs below, highlight elements of a supportive and stable regulatory framework that would ensure that EIIs successfully transition to a low-CO_2 economy while maintaining basic materials production, which is essential to all and in particular green value chains, in Europe.

Protecting against unfair international competition and ensuring a global level playing field in the EU and multilateral trade policy

The transition of EIIs to low-CO_2 economy will be a high risk operation which may increase their exposure to unbalanced international competition, even if most framework conditions are fulfilled.

It is therefore essential to secure a level playing field from direct and indirect carbon costs through the EU and multilateral trade policy. Moreover, this process needs to be accompanied with EU protection of EIIs from unfair trade practices and factors that can harm the international competitiveness of companies.

Full carbon leakage protection from both the direct and indirect costs of the EU ETS

With ETS prices expected to rise significantly in Phase IV, the need for a more adequate carbon protection scheme will be greater in Phase IV of the EU ETS. Thus, the implementation of the revised EU ETS Directive shall ensure that at least at the level of the average of the best 10% installations there is no additional direct or indirect carbon cost.

- This requires effective provisions in the legislation as well as in the implementing measures on carbon leakage and benchmarks.
- Compensation of indirect carbon costs: the overall legal framework (including the ETS Directive and relevant state aid rules) should enable full compensation of indirect costs in all member states, without reductions, digressive application or any other arbitrary restrictions. The current system, which provides for only partial, digressive and voluntary compensation is inadequate in this aspect and can harm the viability of high electrification low-CO_2 pathways for EIIs.

A large and ambitious mission oriented RD&I program for industrial low-CO_2 technologies

The transition to a low-CO_2 economy in a highly competitive, globalized world will be very cost-intensive. This will require the realisation of a large and ambitious mission oriented RD&I program to:

- Stimulate the development of breakthrough technologies and higher electrification.
- Fund industrial demonstration and scale-up. Finance to enable the fast realisation of demonstration plants at industrial scale is an important prerequisite. By 2030 the most promising technological options should have been thoroughly demonstrated at industrial scale.
- Further R&D support from public sources will be essential. This includes the use of Public-Private-Partnerships (PPPs) to focus R&D efforts and to enable risk sharing for investments for demonstration of innovative technologies.
- It will also be necessary to ensure that the required financial support underpins collaboration between industry, government and research institutes and comes with lower administrative burdens.
- Include low CO_2 technologies for EIIs into a new mission within Horizon Europe:
- *'Low-carbon industry transition'*

Competitively priced, carbon-neutral energy

It will be essential to ensure that EIIs have access to competitively priced, carbon-neutral energy on the road to a low-CO_2 economy. Building such a supportive regulatory framework might also entail deregulation in terms of current policies which might stand in the way of higher electrification (including use of H_2). This includes indirect costs under the EU ETS which are seriously deterring investments in (new) processes that require high amounts of electricity and other high regulatory costs related to electricity consumption by EIIs across the EU. Secure supply of competitively priced, carbon-neutral energy will require the EU to:

- Construct a comprehensive strategy for the development of a full range of low- carbon and carbon-neutral energy carriers and related infrastructures and storage.
- A fully market-based and market responsive framework that delivers cost efficient low CO_2 energy.
- Ensure a positive regulatory framework for Power Purchase Agreements (PPAs) and long-term power contracts.
- Adequately value industry's role in balancing the profile of electricity markets.

Ensure that policies to moderate energy consumption are compatible with growth and GHG emissions reductions

A growth-compatible energy efficiency policy is needed that does not unnecessarily limit the energy consumption of EIIs. For instance, an energy efficiency target formulated as an absolute limit on energy consumption and covering industry's energy demand could also become counterproductive to EIIs' efforts to reduce their GHG emissions.

- While industry will continue to reduce its energy intensity in an incremental manner, if the industry must significantly reduce emissions, its low-carbon power consumption is expected to increase dramatically mostly due to the electrification of processes. The current formulation of the EU energy efficiency ambition, i.e. limit of primary and final energy consumption, puts the industry in front of a dilemma and risks limiting the uptake of low-carbon solutions.
- A more flexible consumption pattern of EIIs may support grid stability but reduces energy efficiency on the company level. Energy efficiency policy should take into account the trade-off between flexible consumption by EIIs and energy efficiency measured in terms of intensity.
- The decarbonisation of the energy sector goes hand in hand with GHG reductions in energy intensives sector. The global competitiveness dimension should be put on an equal footing with other dimensions in the governance of the Energy Union.
- Long-term low-emission strategies must be based on strong data and thorough bottom-up feasibility and impact assessments including effects on industry.

Reconsideration and a better alignment of the environmental state aid guidance

Some of the support instruments mentioned in this contribution and in particular specific support by Member States to assist energy intensive industries with financing CAPEX and mitigating OPEX might not be covered by the current scope of environmental & energy as well as R&D state aid guidance. Moreover, the present framework (2014-2020) included in the Energy & Environment Guidelines provides protection to industries from the surcharges of renewable energy. However, the lack of predictability of costs post 2020 acts as a disincentive for future investment. This needs to be put in place to maintain a level playing field with importers for industries that compete globally and for which electrification and other low-carbon technologies are part of the planned solutions towards a low-carbon EU economy. Therefore, it is recommended that these guidelines be reconsidered and aligned with industrial low-CO_2 transition.

Industrial symbiosis and a circular economy through the effective combination of energy recovery and recycling

Industrial symbiosis and enhanced materials efficiency (e.g. energy recovery and recycling) are essential elements to enhance the transition to a low-carbon economy. EIIs can play an important role here through:

- Support for EIIs that seek to collaborate and extract opportunities for symbiosis which will in turn preserve and strengthen European value chains.
- Ensuring a level playing field for the use of biomass waste by removing subsidies that favour one industry over another.
- Facilitating access to raw materials and enhancing waste recycling and the use of by- products. More efforts are needed to improve the sorting and recovery of valuable materials from waste streams whose recyclability potential is still untapped and a higher quality of the recovered waste can be achieved.

- A structured waste policy should recognise and reward the benefits of an effective combination of energy recovery and recycling where this combination is justified by life-cycle thinking on the overall impacts of the generation, management and fate of specific waste streams.
- Acknowledgement that EIIs are also asked to reduce other emissions (e.g. VOCs) next to greenhouse gases and that the share of complex recycling materials will increase in the future and that both these trends may cause a growing energy consumption, namely electricity.
- The opportunity to design EU product standards for low-carbon materials, taking into account a whole life-cycle approach. European standards (ENs) could also be used in public procurement and to export European low-carbon technologies and products. These low-carbon product standards can also be helpful towards a global level playing field on import/export at product level to correct for the embedded carbon in the products which are internationally traded.
- Strengthen efforts to encourage the consumer's role (awareness, understanding, involvement, transaction) by further promoting and expanding a European system of labelling.

Streamlining of the permitting procedures allowing a timely and predictable set of infrastructures and interconnections

Beyond the technological and cost challenges there are other important factors that will influence the practical application of CCS, for instance due to legal provisions preventing deployment of CCS as well as possible lack of public and political acceptance of both storage and transmission.

- Permitting of CCS (and other low-CO_2) infrastructure must be streamlined, timely and predictable across the EU.
- Facilitate the development of large, medium and small CCS/CCU/H_2 hubs and clusters in Europe and support infrastructure and interconnections investments at a European level (e.g. European industrial projects of common interest).
- Identify and support pathways for combining CCU/S with other relevant technologies through the right public policies and information to the broader public.

Transparent and harmonized accounting framework and guidelines for CCU across sectors and value-chains to allow business cases to emerge

There is need for an agreed and transparent accounting framework and guidelines for CCU (including in the EU ETS) across sectors and value-chains to allow business cases to emerge. The mitigation impact of CO_2 utilisation and valorisation technologies requires an appropriate evaluation based on a qualified Life Cycle Assessment. All contributions to GHG emissions have to be taken into account in order to quantify avoided CO_2 emissions by conversion of CO_2 as an alternative carbon source as compared to conventional production pathways. System boundaries for the evaluation have to be carefully defined for each case.

6. CONCLUSIONS: TOWARDS AN INTEGRATED EUROPEAN INDUSTRIAL STRATEGY ENABLING A CARBON NEUTRAL EUROPE

As enabling materials industries, energy intensive sectors form the backbone of the European economy. The flow of materials to and from the energy intensive industries forms a highly dense, integrated network with each other and every other sector of the economy. The energy intensive industrial sector in Europe is oriented largely towards domestic European consumption - around 80% of the goods produced by the EIIs are traded all over Europe.[199] Not only do EIIs enable the European economy, but looking ahead, are needed to enable a carbon neutral Europe and help address climate change adaptation. The fundamental and even strategic links between EII and other sectors forms the basis of the manufacturing economy.

Between 1990 and 2015, EII's have reduced their GHG emissions by 36% (-375 Mt), contributing 28% to the total emission reductions by the EU (-1331 Mt) while their share of total direct GHG emissions in 2015 represented only 15% of EU total GHG emissions (excl. LULUCF). In the same period, energy intensity declined by 39% across all industrial sectors together [200] while the share of energy intensive industries in the EU's final energy consumption fell from 23% to 19% (1990-2016). Not only have EII's more than disproportionately helped reduce emissions from their own sectors, but have also contributed to emissions reductions in other sectors like transport, buildings, waste and power generation. EIIs have also been at forefront of circularity - next to virgin raw material use, recycled materials form a high share of their raw material inputs.

However, EIIs also face significant vulnerability when it comes to economic and external shocks. Between 2000 and 2016, output fell in all sectors (except the chemical sector[201] and pulp and paper industry[202]) while in some EII like steel, cement, refining, pulp and paper, glass, ceramics, and lime, large industrial closures ensued. To date, with the exception of only the chemical sector, no other EII has achieved pre-crisis level production. While GVA amongst the EII[203] as a whole grew 19% (2000-2016), the rest of the EU economy grew faster. Moreover, some EII remain highly dependent on raw material imports into the EU: the vast majority of ores used by the steel, non-ferrous metals and ferro-alloys and silicon sectors are imported.[204]

EIIs have embraced the need to transition to a low-CO_2 economy and have played a constructive role by developing solutions for their sectors while also assisting other parts of the economy through their products, symbiosis, services to energy, and enabling higher levels of circularity and waste valorisation. Important progress has been made in the development of low-CO_2 breakthrough technologies for EII processes by privately-led R&D initiatives from individual companies and enabled by continued European R&D support under different programmes. For each sector multiple technology options are being developed towards significant GHG reductions.

199 Crisp, J., 2017
200 CEFIC, 2017
201 Eurostat, 2018d
202 CEPI, 2018a & b
203 Eurostat, 2018c
204 CEFIC, 2018 | Feedstock can make up as much as 60% of the production cost in the European chemical industry (however, the chemicals sector enjoys access to key raw materials (e.g. for oil and naphtha) at zero or low import duties.

An extremely broad and rich compendium of sectoral technology studies, low-carbon roadmaps and pathways for and by EIIs has been published over recent years. EIIs already play an important role in the circular economy and this role will increase in the future given a conducive regulatory environment leading to major economy-wide cost savings. EIIs have also explored industrial symbiosis, clustering and synergies with non-industrial sectors with a potential for significant energy savings and materials efficiency, while in the areas of energy transition and circular economy, new business models are being explored.

While EIIs are a part of the solution, there is need for EU support. The gestation time of breakthrough technologies is long and many have not reached industrial scale demonstration level. It is important that all the technology pathways get their fair chance in view of the wide range of economics, technology readiness and development stages in the context of policy choices and financing strategies. Moreover, much higher levels of final electricity demand are to be expected if industrial low-CO_2 technologies are deployed across the EU. A decarbonised power sector would have a major impact on indirect CO_2 emissions reductions. Indeed, for the most electro-intensive industries, decarbonised power would lead to up to 90% reductions in overall emissions. Transition to higher levels of electrification can create a virtuous cycle between the EU's renewable energy and industrial transition under the right conditions. Finally, greater circularity and digitisation can lead to the development of new business models together with the need for skills development.

However, for the EII's to successfully transition to a low-CO_2 economy while maintaining production in Europe, certain framework conditions will need to be met, especially given long investment cycles amongst EIIs and the fact that most EIIs operate in highly competitive and dynamic international context.

First, continued protection of competitiveness is vital to ensure high levels of investment and maintenance of production in the EU. Second, a large and ambitious mission-oriented R&D and innovation support program is needed to accompany the most promising low-CO_2 technologies to industrial scale demonstration level by 2030 at the latest and help achieve CAPEX and OPEX cost reductions in key enabling low-CO_2 processes. Third, electricity demand amongst EII can be expected to rise significantly in the next decades especially with the deployment of low-CO_2 technologies. It will be crucial to ensure not only supply security but that the new electricity supply is low-CO_2 and competitively priced. A strategic approach that links the EU's energy transition with the transition of energy intensive industries is therefore required, one where (increasing) regulatory costs do not deter investments in new technologies and where long term contracts (e.g. renewable PPAs) are encouraged and facilitated.

Fourth, a mapping and subsequent development of the necessary infrastructure for hydrogen and CCU/CCS in Europe as well as European industrial projects of common interest is initiated.

Fifth, addressing the CAPEX-OPEX challenge for industrial low-CO_2 transition will require a mix of instruments with the goal to increase industrial investment levels *well above* their current rate in the EU especially given that investment decisions in low-CO_2 processes will not happen if CAPEX is unaffordable and OPEX is not competitive. In the same regard, measures like permitting accelerated depreciation of new installations and other tax incentives can be explored for addressing additional costs (CAPEX+OPEX) for producers given new industrial low-CO_2 process plant constructions and refurbishments will likely ensue at the same industrial sites. Finally, European environmental state aid guidance will have to be reviewed to align itself with the need to enable low-CO_2 technologies to be developed and deployed in Europe.

Sixth, while Europe is already a success story when it comes to steel, non-ferrous, paper or glass recycling for instance, important challenges remain in other value chains and in particular with regard to maintaining the quality of basic materials in recycled product streams.

Finally throughout this contribution, regulatory barriers and opportunities have been identified which will determine whether EIIs will thrive and invest in the low-carbon transition Together these barriers and opportunities form nine key elements that would establish a supportive and stable regulatory framework needed to ensure that EIIs successfully transition to a low-CO_2 economy while maintaining basic materials production, which is essential to all and in particular green value chains, in Europe:

- Protection against unfair international competition towards a level playing field
- Full carbon leakage protection from both direct and indirect costs of the EU ETS
- A large and ambitious mission oriented RD&I program for industrial low-CO_2 technologies, including funding for industrial demonstration and scale up
- Competitively priced, carbon-neutral energy
- Consistency within the energy and climate policy framework to ensure that energy consumption and low-carbon policies are compatible
- Reconsideration and a better alignment of the environmental state aid guidance
- Industrial symbiosis and a circular economy through the effective combination of energy recovery and recycling
- Streamlining of the permitting procedures allowing a timely and predictable set of infrastructures and interconnections
- Transparent accounting framework for CCU across sectors and value-chains to allow business cases to emerge

WHERE WE ARE

The existing framework for energy intensive industries to move ahead with enabling a low- carbon transition in Europe is unfortunately not adequate at this moment. The R&D gap towards demonstration and commercialisation of low-CO_2 technologies is not fully addressed and there remain major challenges to bring down CAPEX and OPEX of new technologies. Infrastructure that could enable the roll out of new processes across Europe is barely present and the financing instruments at EU and Member State levels to facilitate investments are insufficient. Furthermore, existing regulations can have a counterproductive effect. For instance, high and rising electricity prices as a consequence of EU and national regulations could close off the road to higher levels of electrification in energy intensive industries. Finally, the continued importance of maintaining a competitive industrial base is not well aligned across all policy areas, leading to an important risk of investment leakage (including of low-CO_2 investments).

THE WAY FORWARD – A NEW INDUSTRIAL STRATEGY

The challenge of further significant greenhouse gas emission reductions in energy intensive industries, especially given its urgency and scale and with regard to the long investment cycles of EIIs, is substantial. Therefore, a new and integrated EU industrial strategy for EIIs as part of a competitive low-CO_2 transition is needed. This must include:

- The design and implementation of a EU flagship mission oriented R&D programme that addresses the main challenges towards competitive low-CO_2 processes in energy intensive industries. Adequate support for demonstration of advanced low- CO_2 technologies towards market readiness.
- The strategic alignment of the EU's energy and industry transitions in particular with regard to ample and competitive supply of low-CO_2 electricity to energy intensive industries.
- Development of adequate financing mechanisms to face the high CAPEX that comes with low-CO_2 process investments including support for replacement of existing and productive assets with low-CO_2 processes. A state aid regime that acknowledges the size and scope of the industrial low-CO_2 transition.
- Urgent strategic industrial low-CO_2 infrastructure planning with a focus on regional and transnational industry clusters and industrial symbiosis and the development of EU industrial projects of common interests.
- Smart regulatory instruments that can assist with lead market creation for low-CO_2 products and processes. This includes the use of public procurement and development of low-CO_2 standards for products.
- Finally, during the transition continued protection for energy intensive industries should be provided to safeguard competitiveness and investments in Europe.

AN EU STRATEGY FOR LONG-TERM EU GREENHOUSE GAS EMISSION REDUCTIONS WILL ONLY BE SUCCESSFUL IF IT FULLY EMBEDS SUCH INDUSTRIAL STRATEGY.

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LIST OF ABBREVIATIONS

BAU	Business As Usual
bcm	Billion cubic metres of natural gas
Bn	Billion
C&DW	Construction and Demolition Waste
C2C	Cradle to Cradle
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CFCs	Chlorofluorocarbons
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DRI	Direct-reduced Iron
EIB	European Investment Bank
EIF	European Investment Fund
EII	Energy Intensive Industries
EJ	Exajoule (1018 J)
EPR	Extended Producer Responsibility
EU ETS	EU Emissions Trading System
EU	European Union
EUR	Euros
E-Waste	Electronic Waste
GHG	Greenhouse Gases (CO_2, CH_4, N_2O, O_3, CFCs, HFCs)
GSCM	Green Supply Chain Management
GVA	Gross Value Added
GWe	Gigawatt Electrical
GW	Gigawatt
H_2	Hydrogen
HFCs	Hydrofluorocarbons
HV	High Voltage
Ktoe	Kilotonne of Oil Equivalent
kWh	kilowatt hours
kW	Kilowatt
LCOE	Levelized Cost of Energy
LED	Light Emitting Diode
LPG	Liquified Petroleum Gas
LULUCF	Land Use, Land Use Change and Forestry
M^2	Meters squared
Mt	Million Tonnes
Mtoe	Million Tonnes of Oil Equivalent
MWh	Megawatt hour
N_2O	Nitrous oxide
Nm^3	Normal Cubic Meter
N	Nitrogen
O_3	Ozone
OPEX	Operational expenditure
p.a.	Per annum
PPA	Power Purchase Agreement
PPP	Public-Private-Partnership
PVC	Polyvinyl Chloride
R&D	Research and Development
R&I	Research and Innovation
RTO	Research and Technology Organisation
SILC	Sustainable Industries Low Carbon

SME	Small and Medium-sized Enterprises
SMR	Methane Steam Reforming
SPIRE	Sustainable Process Industry through Resource and Energy Efficiency
TBM	Take Back Management
TRL	Technology Readiness level (see Annex I)
T	Temperature
TWh	Terawatt hour (106 MWh)
WACC	Weighted Average Cost of Capital

ANNEX: HORIZON 2020 DEFINITION OF TECHNOLOGY READINESS LEVELS (TRLS)

TRL 1 Basic principles observed

TRL 2 Technology concept formulated

TRL 3 Experimental proof of concept

TRL 4 Technology validated in lab

TRL 5 Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 System prototype demonstration in operational environment

TRL 8 System complete and qualified

TRL 9 Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

ADDENDUM: OVERVIEW OF ENERGY INTENSIVE INDUSTRIES' LOW-CO_2 TECHNOLOGIES, ROADMAPS, PATHWAYS AND STUDIES

See separate file: Industrial Value Chain: *A Bridge Towards a Carbon Neutral Europe - Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions. Addendum: Overview of energy intensive industries' low-*CO_2 *technologies, roadmaps, pathways and studies.*

European energy intensive industries (EIIs) quintessentially form the foundations of the European economy. As enabling materials industries, they link to every possible economic sector, including each other, forming an intricate arterial system of value chains. The energy intensive industrial sector in the European Union (EU) holds strategic importance given that around 80% of the goods produced by the EII are consumed all over Europe.

This report represents the joint contribution from 11 European Energy Intensive Industries (EIIs) - iron and steel, cement, chemicals and fertilizers, refineries, non-ferrous metals, ferro-alloys and silicon, pulp and paper, ceramics, lime, and glass - to the European Commission's Strategy for long-term EU greenhouse gas emissions reductions.

The goal of this contribution is to highlight the constructive and solutions-oriented role that the EIIs have been playing, determine 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.

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