STUDY

Requested by the ITRE committee

Energy-intensive industries

Challenges and opportunities in energy transition

Policy Department for Economic, Scientific and Quality of Life Policies
Directorate-General for Internal Policies
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PE 652.717– July 2020

EN

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Abstract

Energy-intensive industries need to reach climate neutrality by 2050. This study describes the technologies available for the decarbonisation of the iron and steel, chemicals, refining and cement industries as well as the existing financial instruments. Technology and policy roadmaps are presented to help shape the Green Deal and enhance the transition to a climate neutral European industry.

This study was provided by the Policy Department for Economic, Scientific and Quality of Life Policies at the request of the committee on Industry, Research and Energy (ITRE).

This document was requested by the European Parliament's committee on Industry, Research and Energy (ITRE).

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Manuscript completed: May 2020
Date of publication: July 2020

This document is available on the internet at:
http://www.europarl.europa.eu/supporting-analyses

CONTENTS

LIST OF ABBREVIATIONS

BTA	Border Tax Adjustment
CAPEX	Capital Expenses
CCS	Carbon Capture and Storage
CCU	Carbon Capture, Utilisation
CCUS	Carbon Capture, Utilisation and Storage
COSME	EU programme for the Competitiveness of Enterprises and SMEs
CO_2	Carbon Dioxide
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EFSI	European Fund for Strategic Investments
EGD	European Green Deal
EGDIP	European Green Deal Investment Plan
EII	Energy-intensive Industries
EEII	European Energy-intensive Industries
ESIF	European Structural and Investment Funds
EU ETS	European Union Emission Trading System
EUTL	European Transaction Log
GATT	General Agreement on Tariffs and Trade
GHG	Greenhouse Gases
HLG EII	High-Level Group on Energy-Intensive Industries
H2020	Horizon 2020 programme
LCA	Life Cycle Assessment
MRV	Measurement, Reporting and Verification

N_2O	Nitrous Oxide
OPEX	Operational Expenses
PI	Process Intensification
SME	Small and Medium-sized Enterprise
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
WTO	World Trade Organisation

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction and background

In March 2020 the European Commission presented its proposal for "A New Industrial Strategy for Europe". This document underpins the important role of industry in the transformation towards a carbon-neutral economy. Industry has to reduce their own carbon footprints and at the same time accelerate the transition by providing affordable, clean technology solutions. These efforts should be supported by policies and financial instruments at EU and national level, as well as by the private sector.

Energy-intensive industries (EII) deserve special interest as their large carbon footprints make their transformation towards a carbon-neutral form of production challenging. This study explores how EU energy-intensive industries can transition to a climate-neutral economy while maintaining, and ideally improving, its global competitiveness.

Competitiveness of energy-intensive industries is a challenge

Unequal carbon costs have long been considered as harming the global competitiveness of European EII, resulting in carbon leakage. So far, however, EII have not shown signs of deteriorating competitiveness as a result of carbon costs. At the same time, they have not yet increased their energy productivity in a way that they could absorb rising energy and carbon prices in the future. In the longer run, however, we expect that more and more countries will introduce carbon pricing or other, comparable climate policies. Competitiveness in a decarbonising global economy will then primarily be determined by the capacity to deliver products with drastically reduced emissions. Shielding EIIs from higher carbon costs may therefore only be a short-term fix and may risk leading them into a lock-in. A more long-term oriented policy framework should build up or extend leadership in the area of low-carbon industrial technologies.

The required CO_2 reduction technologies are in most cases mature technologies

There is a range of technologies available that can guide Europe's EIIs towards carbon neutrality by 2050. These can be divided into those that

- reduce the CO_2 emissions of current processes: energy efficiency, carbon capture and storage (CCS);
- replace fossil fuels for production: by electrification, biomass, low-carbon hydrogen or other synthetic fuels; or
- develop new production pathways with a lower CO_2 footprint: carbon capture and utilisation (CCU), process intensification and circular economy.

All these technologies are mature, but high upfront capital costs and higher operational costs create an effective barrier to their uptake.

CO_2 reduction technologies are more costly but the impact on competitiveness is limited

Carbon-neutral energy is often 2 or 3 times more expensive than fossil-sourced energy. There are cheaper options such as energy savings or CCS at concentrated sources and innovation may still bring down these costs. But even if energy costs of industry were to double, the carbon neutral economy would only result in price increases of 2-11% in the most energy-intensive sectors such as refineries, cement, fertilizers and iron and steel. As companies have 30 years to adjust to these price increases, it is not likely that this would wipe out the European base of energy-intensive industries.

Missing infrastructure and regulatory framework are major hurdles

Successful uptake of these technologies is therefore dependent on other factors that to some extent lay outside the scope of influence of individual companies. Governments should assist in establishing rules for sustainable biomass use and providing plenty of renewable electricity sources to satisfy growing demand in industry. In addition, many of the technologies require substantial investments in infrastructure for electricity, hydrogen and CO_2 networks. Such infrastructure is often beyond the scope of individual companies and therefore needs to be accompanied by government support for the construction and operation of such networks.

Existing financial instruments fall short of the objectives

The present policy mix in the EU uses regulation, price instruments and subsidies. The EU Emissions Trading System (EU ETS) is the main policy instrument that puts a price on CO_2 emissions for the EIIs. Even though prices have increased in the last two years, they are still a factor 4 below what could be considered as an efficient price path towards carbon neutrality in 2050 (if the EU ETS were the only instrument guiding the transition). Such high carbon prices, however, could have serious adverse impacts on the competitiveness and financial viability of EIIs.

Support for low carbon investments can bring down these costs. Currently, there are many funding and support instruments available for energy-intensive industries such as Horizon 2020, the European Fund for Strategic Investments (EFSI), Programme for Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME), European Structural and Investment Funds (ESIF), Just Transition Fund and the Innovation Fund following from the EU ETS. However, even though these funds can generate billions of Euros support annually for the EIIs, the investment needs are much larger.

The expected wave of investment support has to promote low-carbon investments

Over the coming months, governments across Europe are expected to launch stimulus packages to revive their economy and to restart economic development and growth. This presents a unique opportunity to accelerate investments needed for the transition of energy-intensive industries towards carbon neutrality. Much of the investment for transitioning to a climate-neutral economy will need to happen in the 2020's – which also means that investments supported under the expected wave of stimulus measures will need to be compatible with the transition to climate-neutrality. By contrast, programmes need to avoid any investment incentives that cement the current structures in energy-intensive industries, and thus produce more stranded assets over the long run.

Creating market demand for low carbon products is key

While subsidies can be helpful to accelerate change, in the long run Europe cannot subsidise its industry all the way to carbon neutrality: the transition needs to be driven by market-based incentives. Our analysis shows that the redesign of fossil fuel-based products (such as bio-based plastics, synthetic fuels and recycled cement) is key in the transition towards a low carbon economy. Demand for carbon neutral products should be encouraged through green public procurement and product regulations. The strive for a circular economy could be another enabler in stimulating market demand.

CO_2 emissions from burning fossil fuels can be reduced by new processes in the iron and steel sector, and use of hydrogen produced from renewable energy as feedstock in the fertilizer sector and as fuel in other sectors. Heat demand in industry will have to be decarbonised through heat pumps or use of hydrogen or geothermal heat. Emissions that cannot be avoided could still be tackled through CCS or CCU. As retrofitting outdated processes with CCS is not recommended, CCS/CCU should be applied to processes that have unpreventable CO_2 emissions, most prominently in the cement and lime sector and at waste incineration plants.

Without substantially higher carbon prices, the business cases for these transitions may not be attractive and investments into climate-neutral infrastructure run the risk of not being fully utilised. Carbon prices should be near €100/tCO_2 in the short to medium term, increasing to over €250/tCO_2 in 2050. If implemented unilaterally, higher carbon prices come at the cost of deteriorating competitiveness, so they would need to be accompanied by an effective border tax adjustment (BTA) that taxes imports similarly and exempts exports. An alternative is to introduce higher carbon prices by taxing the CO_2 embodied in products, instead of production-based charges. This would also force consumers to take carbon costs into account, and could eventually be administered in a system similar to the VAT where in every production step, the added carbon is being charged.

1. INTRODUCTION

1.1. Background

The Paris Agreement has the objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C. The European Union ratified the Paris Agreement on 5 October, 2016 and submitted its nationally determined contribution (NDC), committing itself to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990 under its wider 2030 climate and energy framework. All key legislation for implementing this target has been adopted by the end of 2018.

In November 2018, the European Commission presented their strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050. The strategy shows how Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for a just transition. In the political guidelines for the next European Commission, Ms von der Leyen stated this ambition as follows: "Becoming the world's first climate-neutral continent is the greatest challenge and opportunity of our times. It involves taking decisive action now. We will need to invest in innovation and research, redesign our economy and update our industrial policy".

In December 2019, the European Commission presented the European Green Deal. In this new growth strategy, the European Commission is committed to becoming the first climate-neutral bloc in the world by 2050. The plan is underpinned by an investment plan (the Sustainable Europe Investment Plan) that will mobilise public investment and help to unlock private funds through EU financial instruments which would lead to at least EUR 1 trillion of investments.

Industry has a leading role to play in the transformation towards a climate-neutral economy. All industrial value chains, including energy-intensive sectors, will be confronted with major challenges. In March 2020, the European Commission presented "A New Industrial Strategy for Europe". This document underpins the important role of industry in the transformation towards a carbon-neutral economy. Industry has not only to work on reducing their own carbon footprints but also accelerate the transition by providing affordable, clean technology solutions and by developing new business models. These efforts should be supported by policies and financial instruments at EU and national level, as well as the private sector. The big question for the coming years is what direction this support should take and how it can be implemented most effectively.

The effectiveness of the support may even becoming more urgent since the Corona Crisis has started. This crisis will lead to substantial economic losses and result in deficit governmental budgets in every European member state. Designing cost-effective climate policy instruments will become an even more urgent feature of future climate policies.

1.2. Aim of the study

The study has the objective to explore how the EU energy-intensive industries can transition to a climate-neutral economy while maintaining, and ideally improving, its global competitiveness.

This research addresses this objective from three angles: technology, business and finance.

1.2.1. Role of technology

- What technologies can support attaining the ambitious mid-century climate targets (e.g. use of biomass, further electrification, Carbon Capture and Storage (CCS), use of low-CO_2 hydrogen, Carbon Capture and Use (CCU), Carbon Recycling, Deep Geothermal, and process intensification?
- What are the possibilities of renewable gas (hydrogen, biogas, synthetic gas, etc.) and what is the role of energy storage in the future energy system? What are the hurdles to their deployment? And how feasible are technological alternatives for the transition period (e.g. alternatives as natural gas and nuclear)?

1.2.2. Role of finance

- How should this transition be financed and what is the role of the EU programmes, such as the current existing schemes for the energy-intensive industries in the EFSI, COSME, Horizon 2020, the European Structural and Investment Funds and the Innovation Fund from the EU ETS? Is support of capital expenses (CAPEX) preferred over support of operational expenses (OPEX)?
- What is the possible role of the Just Transition Fund and Modernisation Funds from the EU ETS in mitigating social impacts from the transition towards a climate-neutral economy?

1.2.3. Role of business

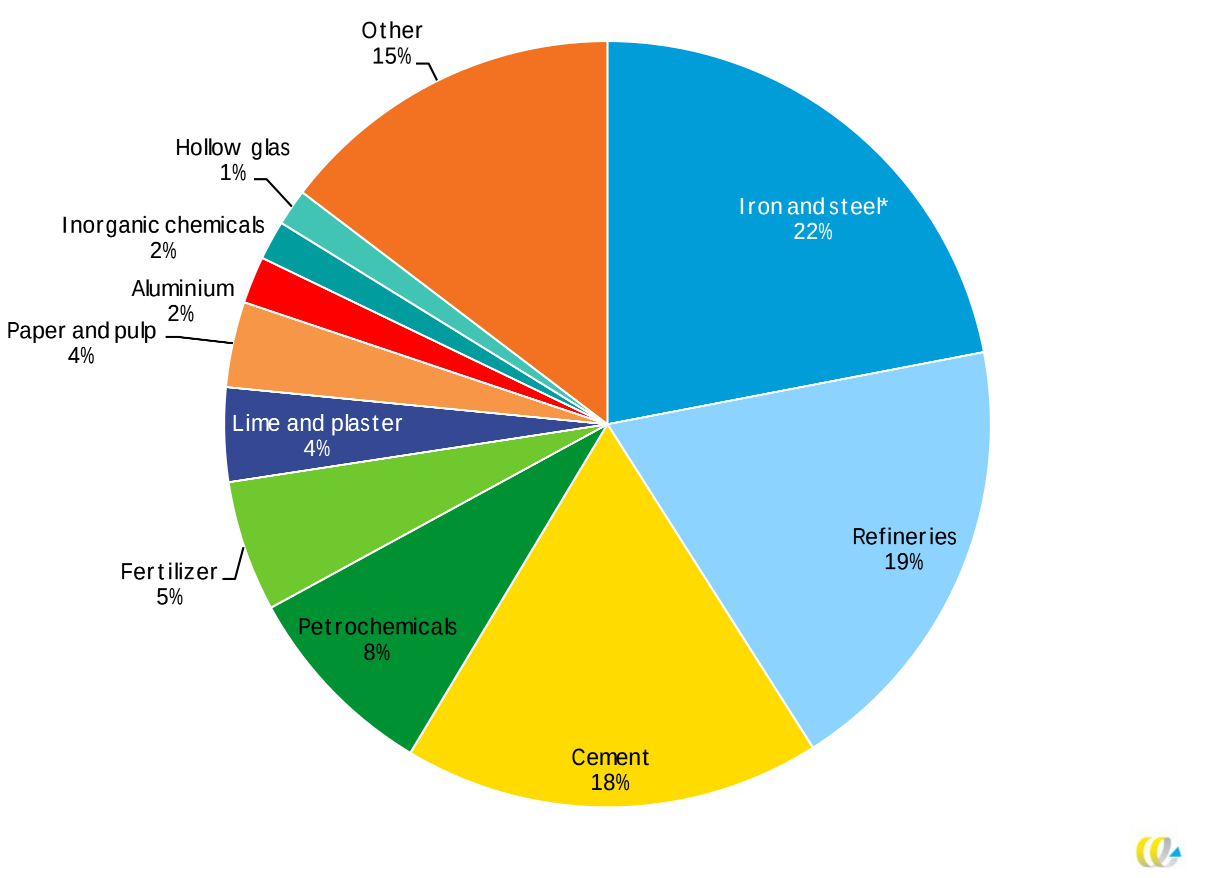
- Which kind of new business models and value chains can be needed to support this transition i.e. required industrial symbiosis for supply chains in CCU?
- How can the decarbonisation of the energy-intensive industries be supported by niche markets/lead markets for low and zero carbon technologies and products?

1.3. Delineation

The scope of the project are the EU's energy-intensive industries (EII). This study cannot address all the issues that are relevant in all necessary detail. As a working definition, we focus on those industrial sectors that are covered in the EU Emissions Trading System (EU ETS). Figure 1 shows the emissions of industrial sectors in the EU ETS, according to the European Transaction Log (EUTL). This figure shows that the Iron and steel sector has the greatest share of emissions followed by refineries, cement, petrochemicals and fertilizer. Together these five sectors make up over 70% of industrial emissions in the EU ETS. These sectors therefore form the core of our technical and financial analysis.

However, these are not the only energy-intensive industries for whom transition to climate neutrality constitutes a challenge. In the treatment of the economic impacts, we will also investigate the situation in the industries that constitute the top-10 sectors in the EU ETS. Next to the aforementioned five sectors these include: lime and plaster; paper and pulp; aluminium, inorganic chemicals and hollow glass. Including these sectors implies that 85% of the industrial emissions in the ETS are included in our analysis.

Figure 1: Share of CO_2 emissions in the total industrial CO_2 emissions in the EU ETS in 2018



Source: EUTL, calculations CE Delft

Notes: * Emissions of the iron and steel sector exclude emissions from burning waste gasses to generate electricity

The analysis in this study will be done at the European level, without going into detail regarding the differences between Member States or between individual companies or locations.

The energy-intensive sectors (e.g. iron and steel, cement and lime, chemicals and refineries) have decreased their greenhouse gas emissions by almost 40% between 1990 and 2017. Major components of this reduction are reduction of nitrous oxide (N_2O) in the chemicals sector and CO_2 reductions in the iron and steel, cement and lime sectors. Although all greenhouse gases contribute to global warming, the abatement technologies are different for each gas. Currently, CO_2 emissions constitute 97% of the total GHG emissions for the four sectors under consideration. Therefore, this report will focus only on reduction of CO_2 emissions in the energy-intensive industries.

Finally, one should notice that this study is executed in a rapidly changing policy context. We have included the policy situation as of the beginning of March 2020. The policy chapter can be found in Section 0.

1.4. Reading guide

The content of this study is that Chapter 2 gives the present background information on the current situation of energy-intensive industries with respect to international competitiveness, climate policy costs and the rapidly changing climate policy context. Chapter 3 presents the technologies that can be applied in the industrial sectors to drastically reduce CO_2 emissions. Chapter 4 investigates the existing financial framework within the EU to accommodate the transition towards a carbon-neutral economy. Chapter 5 then investigates potential policy roadmaps to follow and presents various policy recommendations on the strategy to follow in the next decades.

2. STATE OF PLAY OF THE ENERGY-INTENSIVE INDUSTRIES IN EUROPE

2.1. Introduction

Energy-intensive industries are important sectors for the European economies. Within the sectors iron and steel, minerals, refineries and chemical industries an estimated 3.2 million citizens are employed in the new EU27.[1] This is around 11% of total employment in industry. These four sectors contribute about 15% of total value added of manufacturing in the EU27. Products of these sectors are used in other industries within the EU. The sheer presence of energy-intensive industries within the European Union can be seen as an important competitive advantage for high-tech production, such as in the automotive industry or chemical industries. This fact is also recognised in the Industrial Strategy of the European Commission that is nowadays oriented on value chains; (EC, 2019) see also Section 2.4.

Climate neutrality by mid-century implies a very drastic change in the way energy-intensive industries are producing. This chapter describes both the present and future policy context in Section 2.2 and links this with the potential impacts on competitiveness in Section 0. Section 2.4 draws some conclusions.

2.2. CO_2 emissions and climate policy context for energy-intensive industries

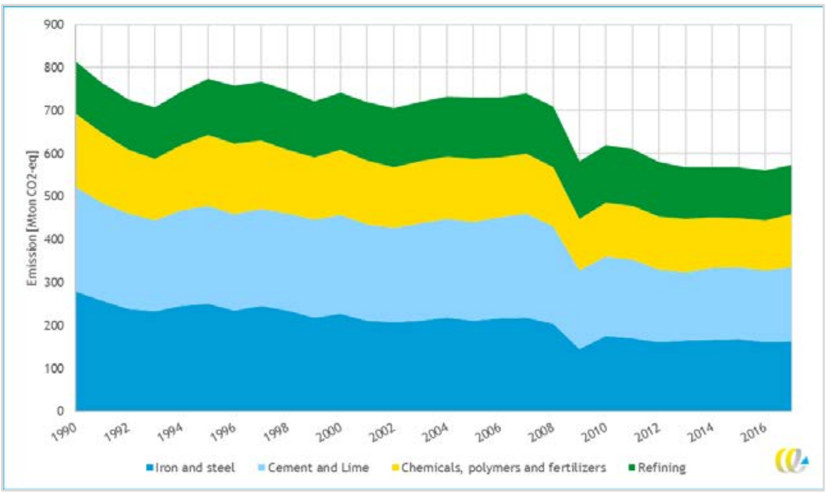
Energy-intensive industries are operating in a rapidly changing climate policy context. After the signature of the Paris Agreement, both the European Commission, the European Parliament and Member States have formulated far-reaching policies with the intention to keep GHG emissions in line with the adopted policy goals.

2.2.1. CO_2 emissions

CO_2 emissions of energy-intensive industries have been fallen significantly over time.

Figure 2 presents the historic figures for the four sectors under consideration.

Figure 2: CO_2 emissions of four core industrial sectors from 1990 until 2017, EU28



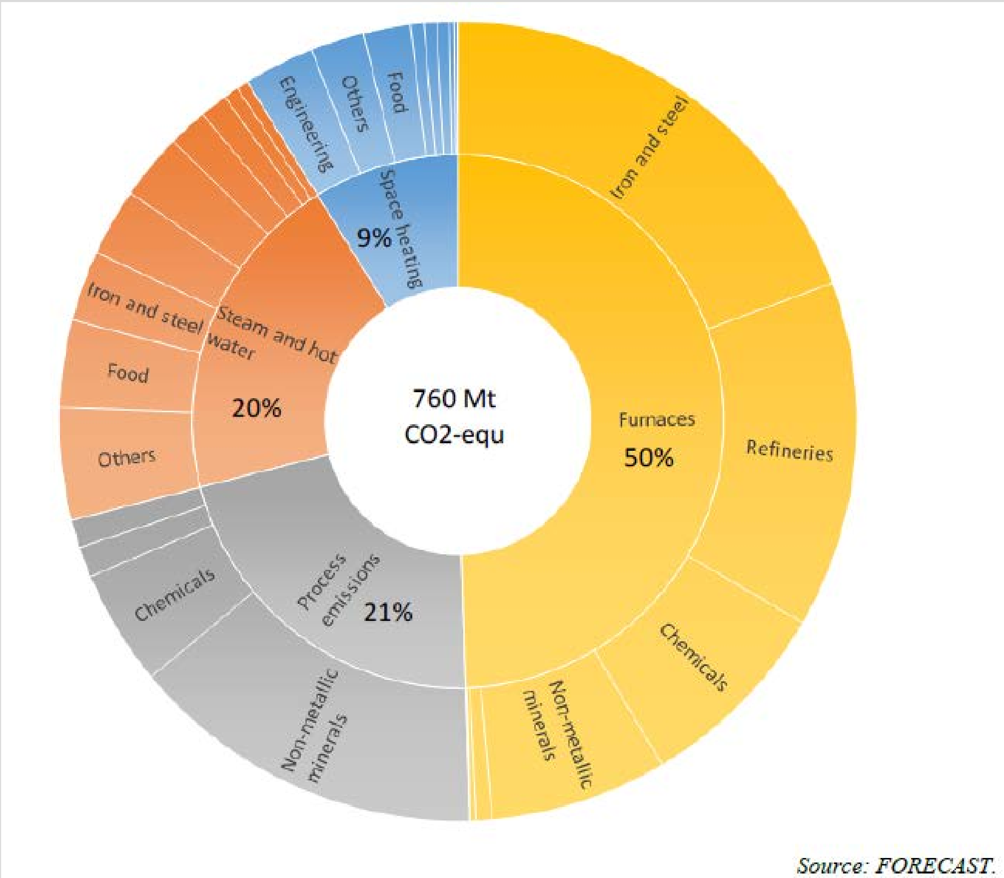
Source: (Eurostat, 2018), calculations CE Delft

[1] Throughout this report we will use data for the whole EU excluding the UK because of Brexit.

In the energy-intensive industries, emissions declined by almost 30% between 1990 and 2018: most profoundly in the iron and steel sector (-41%), followed by the cement and lime (-30%), chemicals (-27%) and refineries (-5%).

Half of all the emissions in the energy-intensive industries are being caused by heating fossil fuels in furnaces for high-temperature processes. Figure 3 provides an overview of the emissions allocated to use in Europe in 2019.

Figure 3: Estimated direct emissions of industry in Europe by end use and sub-sector, note the large share of heat-related emissions



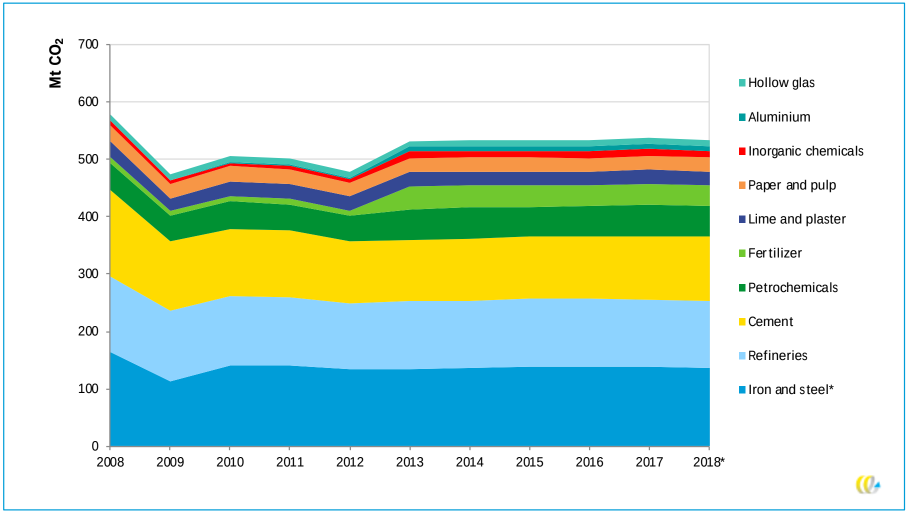
Source: (EC, 2018).

2.2.2. Present regulation

At present, GHG emissions from energy-intensive industries are primarily regulated through the European Emission Trading Scheme (EU ETS). The EU ETS is an EU-wide policy instrument that regulates the E emissions of over 12,000 installations. Participants have to monitor and report their CO_2 and some other GHG emissions and obtain permits for these. Part of the permits are distributed for free to sectors prone to carbon leakage (see Section 2.4), the rest is sold via auctions. The number of permits distributed decreases every year according to the "linear reduction factor", currently 2.2%. Permits can be traded to assure a cost-effective compliance to the required reductions.

Figure 4 shows that the emissions of energy-intensive industries participating in the EU ETS declined between 2008-2012, but since 2013 emission reduction has come to a halt.

Figure 4: CO_2 emissions in the EU ETS from the energy-intensive industries, EU27, 2008-2018



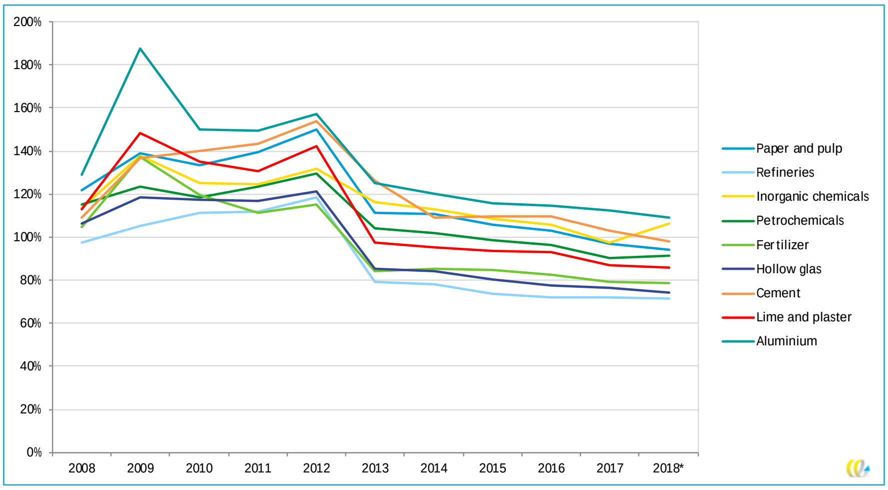
Source: EUTL data, CE Delft calculations.

* Preliminary dataBTA.

The lack of emission reduction is remarkable because since the start of Phase 3 in the EU ETS, energy-intensive industries have gradually received less allowances for free (see Figure 4). Nowadays all sectors, with the exception of the inorganic chemicals and aluminium, need to buy a part of the emission allowances to fulfil their compliance obligations (see

Figure 5).[2] Refineries, on average, had to buy permits for around 30% of their CO_2 emissions in 2018.

Figure 5: Percentage of free allowances compared to verified emissions of the energy-intensive industries in the EU ETS, EU27 data, 2008-2018[3]



Source: EUTL data, CE Delft calculations.

2 It should be noted, though, that most companies still have a large surplus of allowances stemming from the over-allocation of allowances during Phase 2 of the EU ETS (2008-2013).

3 In interpreting the figure, one should notice that >100% implies that the sector receives more free allowances than its verified emissions. During Phase 2 (2008-2012), there was over-allocation to industries, as the fall in emissions because of the economic crisis was not adjusted with a lower allocation of allowances.

The ten energy-intensive industries together faced a total cost of around EUR 1 billion from the net purchase of allowances in the EU ETS.[4] This will gradually increase towards an estimated EUR 5 billion in 2030 because of the changes in Phase IV of the EU ETS (see Chapter 4).

2.2.3. Future climate policy context

In December 2019, the European Commission presented the European Green Deal (EGD). In it, the Commission sketches its strategy to transform the EU into a resource-efficient competitive and climate-neutral economy by 2050. As one key step for implementing the EGD, the Commission proposed a European Climate Law on 4 March 2020. This Climate Law is intended to legally enshrine the goal of climate neutrality by 2050.

The European Green Deal mentions the EII explicitly: 'Energy-intensive industries, such as steel, chemicals and cement, are indispensable to Europe's economy, as they supply several key value chains. The decarbonisation and modernisation of this sector is essential.'[5]

The European Green Deal stresses the need for frontrunners to develop commercial applications of breakthrough technologies in key industrial sectors by 2030. It also underlines the importance of new technologies and their deployment across the internal market.[6] The Innovation Fund that was recently established as part of the EU ETS will contribute to the funding of large-scale innovative projects to demonstrate the use of low-carbon technologies in EII (EC, 2019).

To meet climate targets set in the European Green Deal significant investments and funding are required. To meet funding needs the Commission will present a European Green Deal Investment Plan (EGDIP).[7] Capital for this Investment Plan will be provided by the EU Budget, InvestEU and revenue from the EU ETS. The Commission will also review the role of the Innovation and Modernisation funds as part of the EU ETS review. A Just Transition Mechanism is part of the EGDIP. This mechanism is designed to ensure a fair transition toward a carbon-neutral economy. The focus of this mechanism will be on regions and sectors that depend on fossil fuels or carbon-intensive processes as they are most affected by the transition (EC, 2019). Chapter 4 will review these financial instruments.

Specific for the European Industry, the Commission states that the European Green Deal will support and accelerate the transition to a sustainable model of inclusive growth (EC, 2019). To this end the European Commission has adopted an EU industrial strategy in March 2020 (EC, 2020).[8] This strategy is part of the new circular economy action plan, which aims to stimulate markets for circular and climate-neutral products (EC, 2019). For energy-intensive industries, the plan echoes the objective set in the European Green Deal to create new markets for climate-neutral and circular products, such as steel, cement and basic chemicals. To lead this change, Europe needs novel industrial processes and more clean technologies to reduce costs and improve market readiness. In order to do this, the Commission will support clean steel breakthrough technologies leading to a zero-carbon steel making process. A new chemicals strategy for sustainability will help better protect people and the environment against hazardous chemicals and encourage innovation in the sector to develop safe and sustainable alternatives. The EU Emissions Trading System Innovation Fund will help deploy other large-scale innovative projects to support clean products in all energy-intensive sectors. A Clean Hydrogen

4 Calculated as the average of verified emissions minus allocated emissions multiplied by the average emission price in 2019 (€24/tCO_2) excluding the iron and steel sector.

5 European Commission Communication, The European Green Deal, COM (2019) 640.

6 The Green Deal mentions the following priority areas: clean hydrogen, fuel cells and other alternative fuels, energy storage, carbon capture, storage and utilisation.

7 See the European Commission, press release of 14/01/2020, Financing the green transition: The European Green Deal Investment Plan and Just Transition Mechanism, available at: https://ec.europa.eu/regional_policy/en/newsroom/news/2020/01/14-01-2020-financing-the-green-transition-the-european-green-deal-investment-plan-and-just-transition-mechanism

8 European Commission Communication, A new Industrial Strategy for Europe, COM (2020) 102.

Alliance will be established to accelerate the decarbonisation of industry and maintain industrial leadership, followed by Alliances on Low-Carbon Industries and on Industrial Clouds and Platforms and raw materials.

The Commission will adopt a White Paper by mid-2020 to address distortive effects caused by foreign subsidies in the single market and tackle foreign access to EU public procurement and EU funding. The issue related to foreign subsidies will be addressed in a proposal for a legal instrument in 2021. This will go hand in hand with ongoing work to strengthen global rules on industrial subsidies in the World Trade Organisation, and actions to address the lack of reciprocal access for public procurement in third countries.

By summer 2020, the Commission will present an impact assessed plan to increase the reduction target for 2030 to 50-55% (compared to 1990 levels). By June 2021, the commission will review and where necessary revise all climate-related policy instruments, including the EU ETS (and a possible extension thereof) and the Energy Taxation Directive. A carbon border adjustment mechanism will be proposed in case of divergence between European and worldwide climate ambitions. This mechanism is supposed to protect European energy-intensive industries from competitors that operate with less stringent climate regulations, and thus have an unfair competitive advantage.

2.2.4. High level group

The High-Level Group on Energy-Intensive Industries (HLG EII) developed a Masterplan[9] containing recommendations to manage the transition to climate-neutrality while keeping the EII competitive.[10] These recommendations served as input for the European Green Deal and the EU Industrial Strategy. The HLG EII share the ambition of the Paris Agreement and underline the transformation challenges this ambition implies. The Masterplan gives concrete recommendations on three themes:

- the creation of markets for climate-neutral, circular economy products;
- developing climate-neutral solutions and financing their uptake; and
- resources and deployment.

2.2.5. European Parliament

The European Parliament supports the European Green Deal and underlines its ultimate goal to reach climate-neutrality by 2050.[11] The members of Parliament call for an increase of the 2030 reduction target to 55% compared to 1990 levels, instead of the Commission's 50 to 55% reduction target. In addition, the European Parliament calls for an extra interim target in 2040 on the path to climate-neutrality in 2050.

Moreover, the European Parliament underlines that the Green Deal should aim for a sustainable and competitive economy for all and stresses the importance of a just transition to a climate-neutral economy. In order to prevent carbon leakage, the EP calls for a carbon border adjustment mechanism. European Parliament also underlines and supports the need for a sustainable investment plan to finance investments. The European Parliament regards the availability of substantial public and private investments as a precondition for the success of the Green Deal.

With respect to EII, the European Parliament agrees with the Commission that EII are crucial for the European economy and that their modernisation and decarbonisation of EII is necessary (EP, 2020). The European Parliament also highlights the synergies between climate action and the circular economy in energy- and carbon-intensive industries and calls for an EU-level target for resource efficiency (EP, 2020).

2.2.6. Timelines European policies

Table 1 summarises some key policy documents that will be published by the EC in the upcoming year(s).[12]

[9] Masterplan for a Competitive Transformation of EU Energy-intensive Industries Enabling a Climate-neutral, Circular Economy by 2050 – Report. Date: 28-11-2020.

[10] EU Energy-Intensive Industries' 2050 Masterplan.

[11] European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP)).

[12] For a complete roadmap see: 'Annex to the Communication on the European Green Deal - Roadmap - Key actions'.

Table 1 : Key policy documents to be published by the EC the upcoming years

Date	Action
October 2016	Paris agreement
November 2018	Strategic vision EU ('A Clean Planet for all')
November 2019	Master Plan EII
December 2019	European Green Deal
January 2020	European Parliament support for Green Deal
January 2020	Proposal EGDIP Proposal Just Transition Mechanism
February/March 2020	Proposal European Climate law
March 2020	European Industry Strategy Circular Economy Action Plan
March 2020	European Climate pact
June 2020	Smart sector integration strategy Assessment national energy and climate plans
Summer 2020	EC Impact Assessment Plan for GHG reduction target 2030 Chemicals Strategy for sustainability
Q3 2020	Sustainable finance strategy
2020	Initiatives lead markets for climate-neutral and circular products in EII Proposal to support zero carbon steel-making process by 2030
2021	Proposal Carbon border adjustment mechanism
June 2021	Proposals for revisions of climate-related policy instruments (a.o. ETS Directive, Energy Efficiency Directive, Renewable Energy Directive and Energy Taxation Directive)
2020/2021	EU Strategy on Adaptation to Climate Change

Source: European Commission.

2.3. Impacts on competitiveness

2.3.1. Present situation with respect to competitiveness

Competitiveness is a difficult concept that is often rooted in a wrong interpretation of economics. The famous economist Paul Krugman (1994) argues that:

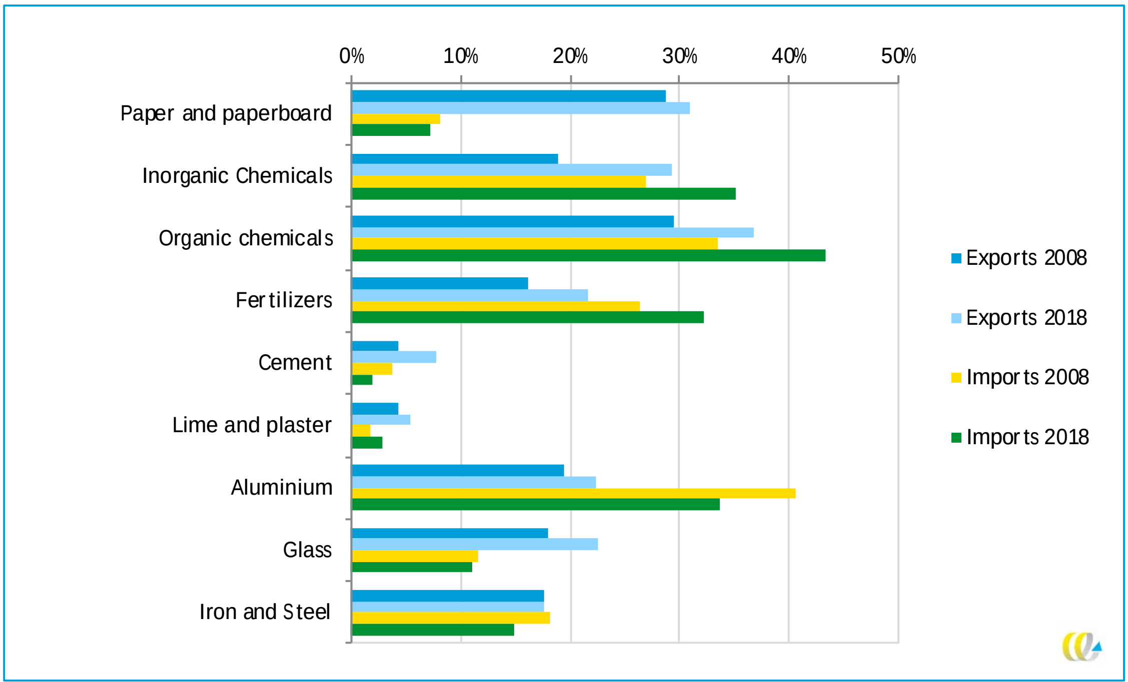
'The doctrine of 'competitiveness' is flatly wrong. The world's leading nations are not, to any important degree, in economic competition with each other'.

As Krugman notes, national economic welfare is determined primarily by productivity in both traded and non-traded sectors of the economy and not by the amount of "competitiveness". The Ricardian theory of trade assumes that countries specialise in their own comparative advantage. There is no model of trade possible where one country dominates in every trade segment – an often implicit vowed aim in many of the advocates of competitiveness.

Having this in mind, we can look a bit more in detail at the potential degree of competitiveness in the EU energy-intensive industries. The international competitiveness is determined by a number of factors – the capacity to develop and deliver innovative, high-quality products that meet the needs of the customers reliably, on time, and at affordable cost. Which of these parameters is most important will differ between products and market segments. Yet for energy-intensive industries, production costs are a particular determinant of their competitiveness. Production costs of the energy-intensive industries have been emphasised a long time but the energy cost component in it has really come into the spotlight since the communication *For a European Industrial Renaissance* from the European Commission in 2014. Specific concern vowed here was that energy costs for the EU industries would endanger their competitiveness in a global market. However, a study by JRC (JRC, 2016) finds that this is not universally true. Production costs of EU industries when compared to major competitors tend to be on the high side for iron and steel, ammonia and methanol production. Production costs in the EU are comparable to the main competitors for cement, ethylene, propylene and copper production. For zinc production, the study finds that the EU has among the lowest production costs. The study shows that EU industries tend to have the highest labour costs; however this cost disadvantage is counter balanced by the high labour productivity, so that the total costs are comparable. A similar advantage has not been achieved by energy costs yet: the study indicates that the energy efficiency of EU industries is only marginally better than that of foreign competitors.

Also if we compare trade flows, we do not witness that European energy-intensive industries have lost competitiveness that would cause a change in relative imports or exports. Figure 6 provides an overview of the situation in 2008 and 2018 with respect to the share of imports and exports to production for nine energy-intensive industrial sectors. First of all this figure shows that some sectors, like cement and lime, are hardly competing on world markets as the shares of imports and exports to production are very small. The figure also shows that for most sectors, both exports and imports have been growing in 2018 compared to 2008, which is showing the influence of globalisation so that more trade takes place. For paper and paperboard, glass production and cement, relative exports have been growing while imports have been falling, indicating that these sectors are probably better able to compete with world competitors. For aluminium, iron, and steel, the relative share of imports has been falling indicating that these industries are better able to compete on the domestic EU market than in 2008. So when we investigate trade flows there is no overall sign of deteriorating competiveness in relative import or export positions. This is similar to conclusions conducted in other research in the past (see e.g. Ecorys and Öko-Institut, 2013).

Figure 6: Share of value of exports and imports in the production value of 9 sectors (2008 and 2018)



Data: Eurostat, DS-066341, retrieved 6 March 2020. For refineries no information was available.
See Annex A for sector delineation.

2.3.2. Present situation with respect to carbon leakage

The risk of carbon leakage has the potential to undermine the effectiveness and support for ambitious future climate policy in the EU. Carbon leakage occurs when, as a result of stricter climate policy in one country, emission-intensive production activities increase in another country with less stringent climate policy. As a result, part or all of the emission reduction achieved in one country is compensated by increases somewhere else. In theory, carbon leakage can only occur if emission move from a country with an absolute ceiling (cap) on their CO_2 emissions to a country that has not capped their CO_2 emissions with an absolute ceiling. If emissions would move from one capped system to another capped system (e.g. from Germany to Norway) there can be no sign of carbon leakage.

Carbon leakage is a complex issue and highly relevant in the context of future climate policies. Carbon leakage can occur through various channels, but the most debated channels in the political arena are the impacts on trade (through productivity and market shares) and the impacts on investments (through impacts on profits margins). These short- and medium term impacts are largely intertwined: if companies in the EU lose market shares because of climate-oriented policies, their investment climate will also be negatively affected in the end.

The theoretical and empirical economic literature is not uniform in their conclusion to what extent carbon leakage has occurred so far because of climate policies or may in the future. For example, Ecorys and Öko Institut (2013) concluded that carbon leakage so far could not be evidenced by the data from sectors participating in the EU ETS. In investigating asymmetric energy prices, Sato and Dechezlepetre (2015) concluded that net exports may be negatively affected by energy price differentials, but that the impact is small. They state that their analysis reveals that a carbon price of €40-65/tCO_2 in the EU ETS would increase Europe's imports from the rest of the world by less than 0.05% and decrease exports by 0.2%. In a more recent paper, Garsous and Kozluk (2017) find similar small negative impacts on investments. Therefore, it is exaggerated to suggest that asymmetrical carbon pricing would wipe out European energy-intensive industries.

However, these empirical papers have merely investigated the short-term impacts. Longer-term impacts have not been investigated properly yet, partly because of the model formulation in the studies above, but also because of the fact that asymmetrical carbon pricing is only a recent phenomenon. In the literature, one can find some key factors that may influence the amount of carbon leakage that is to occur (see e.g. AEA and CE Delft, 2011; Climate Strategies, 2016):

a. The extent to which other economies have similar carbon and energy policies in place. If all countries would adhere to the same CO_2 reduction target, there is no carbon leakage by definition. However, as the UNFCCC has identified that countries have "common but differentiated responsibilities", CO_2 reduction targets have to differ between countries and so do carbon costs.

b. The investment and operational costs of the technologies in energy-intensive industries. Such costs can be lowered over time due to learning effects and targeted R&D efforts.

c. Elasticity of substitution for energy, indicating both the substitution between various energy sources (gas, coal and renewables) and the substitution between energy and other factors of production (labour, capital).

d. Trade elasticities (e.g. Armington elasticities), the extent to which goods produced in the EU can be substituted for goods produced in non-EU countries. The trade elasticities tend to be lower for specific niche products. If the EU industry can become carbon-neutral, and if consumers and public procurement is increasingly asking for carbon-neutral products and services, the exposure to international competition can be diminished.

e. Ability to pass the cost of regulatory compliance to consumers (which may depend on market structures). The ability to pass through costs can also be enhanced by increased demand for carbon-neutral products and public procurement.

f. The extent to which companies can use climate and energy policies to rationalise on other parts of their operations. The Porter hypothesis states that higher carbon costs would force companies to reduce existing inefficiencies and even make companies more competitive on world markets (see Porter and van der Linde, 1995). Although there is quite some controversy if the Porter hypothesis holds true from an empirical point of view (see e.g. Brannlund and Lundgren, 2009), the theory suggests that there could exist a path where climate policies would result in lower costs for the society as a whole. This is particular true if in the present situation market failures exist in information, risk perception or property rights (e.g. split incentives) that make present economics not optimal. If climate policies could internalise one of these existing market failures, economies adhering to climate policies could become more competitive.

Therefore, the fear that unequal carbon costs make EU energy-intensive companies to drive out of business and resulting in massive carbon leakage is oversimplified. Moreover, these mechanisms determine whether a sector or industry is prone to future carbon leakage. As these factors differ for each sector, it is difficult to say something generalised about the risk of carbon leakage. This implies that there is a policy risk in addressing carbon leakage, as policies like to make 'equal rules' for sectors and industries avoiding discriminatory measures. In the EU ETS, the interplay between carbon costs and trade intensities determines which sectors are considered to be at risk of carbon leakage and thereby receive free allowances. Yet if the carbon price should continue to increase, the list of factors identified above would indicate that there would be a necessity for a more sophisticated approach. The question whether such an approach can be found is discussed in Chapter 5.

2.4. Discussion and conclusions

At present, energy-intensive industries in the EU27 pay around one billion Euro annually to comply with the EU ETS. This is a small share, representing about 1.4% of the profits of 2017.[13] Nevertheless, carbon leakage concerns have been high on the political agenda since the start of the EU ETS. So far, no significant carbon leakage impacts have been discerned in the literature: expected impacts for carbon prices up to €30-40/tCO_2 seem to be mild, certainly in the short run. However, the literature has not yet properly investigated long-term impacts.

What determines competitiveness hinges crucially on the timeframe for the investigation, and the assumptions about whether other relevant countries will also pursue increasingly ambitious climate policies. In the short to medium term, and in a world with continued discrepancies in climate ambition, climate-related costs will remain an important determinant for competition. Yet it should not be overplayed. European energy-intensive industries have in the past reacted on the rising labour costs with labour productivity increases thereby remaining competitive on the world market. A similar increase in energy and carbon productivity can keep the European energy-intensive industries in pace with the non-EU competitors.

Yet in the longer run, competitiveness in a decarbonising global economy will come to be determined by the capacity to deliver products with drastically reduced emissions – all the more so if other relevant countries pursue strategies of comparable ambition. In this way, shielding domestic EIIs from the pressure to change and innovate is only a short-term fix – and may risk leading them into a lock-in. A more long-term oriented competitiveness policy should rather aim to build up or extend technological leadership in the area of low-carbon industrial technologies, as outlined in Chapter 3.

[13] Calculated on the basis of the difference of verified minus allocated emissions for the sectors paper & pulp, refineries, inorganic chemicals, organic chemicals, fertilizers, hollow glass, cement, lime, iron and steel and aluminium.

3. AVAILABLE TECHNOLOGIES FOR ENERGY-INTENSIVE INDUSTRIES IN 2050

3.1. Introduction

Ambitious climate policies confront energy-intensive industries with a major challenge: to remain competitive on globalised markets while taking steps to drastically reduce their carbon emissions – and with technological solutions for the transition towards a low-carbon economy at different stages of maturity. This chapter provides a concise overview of potential carbon-neutral technologies that could be applied in the energy-intensive industries. It provides an overview of which technologies can support attaining the ambitious mid-century climate targets, investigates the possibilities of renewable energy carriers and provides an analysis into the role of energy storage in the future energy system.

A climate-neutral industry requires a source of climate-neutral energy, as all processes in the energy-intensive industries require energy by definition. This implies that one either has to use a renewable energy source or a fossil energy source using carbon capture. There are no other options available.

These two core-options have to be assisted by two other developments. Firstly, climate neutrality demands that material chains need to be closed to turn them from chains into loops, with the remaining raw materials needs sourced in a climate-neutral way. Secondly, climate neutrality may involve reduced demand.[14] This includes advances both in energy efficiency as well as in material efficiency.

Any emissions that cannot be avoided by switching of the fuel or feed need to be either captured or offset.[15] A key requirement for the majority of technological options for CO_2 reduction is the availability of low-carbon electricity. In this report, the electricity sector is assumed to be carbon-neutral in 2050 although an increase in electricity production is necessary.

3.2. Approach in identification of key technologies

For the technologies, we focus only on technologies available in the most energy-intensive sectors: iron and steel, cement, refineries, petrochemicals and fertilizers. As seen in Chapter 2, these sectors account for over 70% of CO_2 emissions in the EU ETS. The technologies discussed in this report are selected by first studying various sector roadmaps (Eurofer, 2013), (Cembureau, 2013), (EuLA, 2018), (Cefic, 2019), (DECHEMA, 2018), (FuelsEurope, 2018) and existing literature on the decarbonisation of European industry. Using this information, a number of key reduction paths were selected, the technologies of which were further researched for this report.

In our selection of technologies we first investigated technologies that are proven technology, but not (yet) widely applied. In the scores of technology ranking (see Box 1), these would have a typical Technology Readiness Level (TRL) of 8 to 9 (See next page).

Then, in a second round, we identified technologies that would meet each of the following criteria below:

- promising technology with good prospects for scale-up (TRL 6-7);
- large reduction potential; and
- solutions applicable in multiple sectors.

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[14] In terms of physical quantities produced, not necessarily in terms of monetary values.

[15] An example of these so-called ‘process emissions’ is the calcination of limestone to quicklime in cement production: $CaCO_3 \rightarrow CaO + CO_2$.

It is important to mention that there is no 'silver bullet' that could make the entire industry climate-neutral. Instead, a mix of different technologies is required as each process has its specific boundary conditions.

Then, in a third round, we have grouped the various technologies in the following categories of measures:

1. Technologies that reduce the CO_2 emission of current processes:
   - energy efficiency;
   - electrification, using electricity from renewable energy sources;
   - deep geothermal energy;
   - biomass;
   - renewable or low-carbon hydrogen (or other synthetic fuels); and
   - carbon Capture and Storage.
2. New production pathways with a lower CO_2 footprint:
   - carbon Capture and Utilisation;
   - process Intensification; and
   - circular economy.

In this report we will provide for every technology a detailed elaboration of the type of technologies that would fit under these headings, the current status and the potential for 2050. We will discuss the potential impact of each technology on production processes, products and value chains. Furthermore, the analysis will focus on the necessary preconditions and barriers for implementation. In Annex A we will discuss the technologies in all necessary detail. In Section 0 we will summarise the main findings from the Annex A per technology and discuss the application of these technologies in energy-intensive industries.

Box 1 - Technology Readiness Levels

The Technology Readiness Level (TRL) is an indicator of the maturity of a technology.[16] The TRL methodology is developed by NASA and later adapted by the EU to compare applications for the Horizon 2020 programme. Nine categories are being distinguished:

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)

Source: European Commission.

[16] European Commission Decision C(2014)4995.

3.3. Overview of main technologies

3.3.1. Energy efficiency

Energy efficiency is often termed the “first fuel”: the fuel that is not required due to energy savings. Energy efficiency means producing the same products with less energy. Energy efficiency measures are, for example, better insulation, reuse of waste heat, the use of LED lighting and more efficient electrical drives. Application of energy efficiency measures does not radically alter the production process itself and is therefore relatively easy to implement. There is a remaining technical potential for estimated additional savings of 15-25% in 2050 using current technologies (ICF International, 2015) (McKinsey, 2018). However, extensive research has indicated that the main barrier for energy saving is the fact that it is capital-intensive and that this capital competes with other investments in e.g. new production capacity (CE Delft, 2014; ICF International, 2015). Therefore, the economic potential is much smaller. In practice, a simple payback time of three years is already considered not profitable within some companies.

3.3.2. Technologies dealing with electrification

Because electricity will become increasingly decarbonised towards 2050, there is a growing potential for emission reduction in industry by switching from fossil fuels towards electricity. The use of electricity often offers large efficiency benefits as well, for example in the application of heat pumps for low temperature heat. A potential co-benefit is that electrification of industry could help balancing electricity grids by offering flexibility to grid operators. Several commercially available technologies can be implemented to substitute fossil fuels for heat demand: electrode boilers, electrical resistance heating, heat pumps, steam recompression and electric arc furnaces.

These technologies have the potential to electrify the entire steam demand of industry (Schüwer & Schneider, 2018) and can be applied to space heating as well. This implies that these technologies have the potential to cover nearly 30% of industrial CO_2 emissions. On the other hand, industrial scale high-temperature furnaces such as used in the cement industry still need further development (R&D and market experience) to become mature. The main barrier for the immediate deployment of most electrification technologies is economical (TNO, ECN, 2016) as at present OPEX costs is about a factor 2-3 higher (EC, 2019). Besides the higher OPEX, an investment is required of 150-190 k€/MW for an electric boiler up to 3.5-5 M€/MW for a furnace (DNV-GL, 2018) (Berenschot et. al., 2017).

Electrification can also replace production processes or parts thereof, for example electrowinning of iron, where iron is produced by electrolysis of iron ore. The vast majority of industrial processes can eventually be electrified, so that molecules are only required as feedstock and not as fuel.

Even if more low-price and low-carbon electricity were available, infrastructural challenges are substantial as the current electricity grid was not designed for industrial demand and needs to be reinforced which can even worsen the business case if industrial users would have to pay for this. On the other hand, electrification can also lead to benefits for industries as electrification can for example lead to better process controllability, product quality and lower maintenance requirements.

3.3.3. Technologies for deep geothermal energy

Geothermal energy exploits the natural heat produced inside the planet Earth. The deeper the well, the higher the temperature of the water. The depth required for a certain temperature varies greatly with the structure of the ground. An example well could yield 60-80°C at a depth of 2,000 meters, 120-130°C at 4,000 meters and 175-200°C at 6,000 meters (EBN, 2018). With a suitable underground, temperatures of 250°C can be reached. Although these temperatures are too low for the iron & steel and cement sectors, both the chemical industry and refining have significant demand for temperatures of up to 250°C (McKinsey, 2018), (Heat Roadmap Europe, 2017).

Geothermal energy can potentially cover the entire low- and middle heat temperature demand in industry. However, significant development is necessary before deep geothermal energy will be available for industry. Financing cost (CAPEX) is high because of the many risks associated with mainly the early stages of development of a geothermal project: denial of a permit, a dry well, presence of oil and gas, earthquakes during development, contractor bankruptcy and many others. With current costs of low-temperature geothermal projects around 3 times more expensive than fossil fuel alternatives (ultra)deep geothermal has to come a long way before becoming competitive with fossil fuels.

3.3.4. Technologies using biomass

Biomass could completely replace the current fossil energy carriers and feedstocks in the energy-intensive industries, given a sufficient supply. Supply is primarily limited in biomass that consists of "recently absorbed" and that meets sustainability criteria.[17]

The applications of biomass in industry can roughly be divided in three categories: bio-based products, chemicals and energy uses. In light of the limited availability of recently absorbed biomass, it makes sense to use biomass in high value applications first: the cascading of biomass. As an example, wood could first be used and reused in construction, then used as feed for other bio-based products, which can finally be turned into liquid fuels at the end of their life. Cascading can be based on maximisation of economic value of the applications, maximisation of greenhouse gas reduction or other criteria. The principle of cascading would foster the use of biomass in products and chemicals as here the biomass could be used multiple times.

Another criterion to guide the use of biomass would be the availability of alternatives in the transition towards a low-carbon economy. For example, for aviation there are no other options to become carbon-neutral than to use biofuels or synthetic fuels. For energy-intensive industries, most energy uses of fossil fuels can be equipped with CCS or have another route for decarbonisation. However, production of biofuels and biogas could be useful for decarbonisation in other sectors (e.g. maritime/aviation) that have limited possibilities to reduce CO_2 emissions.

Bio-based products conserve the macrostructure of the biomass in the final product. Examples of well-established uses are wood, paper, natural fibres in clothing and straw roofing. However, many of these uses, e.g. lignin as binder in asphalt, would still need further R&D. Bio-based chemicals extract or produce specific molecules from biomass. In general, the closer the product molecule resembles the molecules in the feedstock, the more efficient the process can be (DECHEMA, 2018). The most efficient use of biomass is the production of dedicated bio-based chemicals that do not have a petrochemical counterpart and that closely resemble the feed. With an optimal process design, only limited processing is required, resulting in large CO_2 reduction potentials.

Bio-based products and chemicals still undergo significant development. Production routes that fully valorise the molecular structure of biomass offer larger economical and sustainability benefits than general purpose approaches, but need more R&D to become mature. Bio-based production routes are commonly more expensive than their fossil counterparts.

There is one area where biomass can still be used in energy applications in energy-intensive industries: when combined with CCS (and replanting of biomass), the industry can provide a net removal of CO_2 from the atmosphere, resulting in negative emissions. This is an interesting option especially after 2050.

3.3.5. Technologies using hydrogen

[17] With recently absorbed carbon we mean that biomass from sources that stored their carbon long time ago, like forests, will result in an increase in global GHG emissions as long as the emissions are not captured. Even reforestation leads to a temporary increase in atmospheric CO_2 since it takes many years before an equal amount of CO_2 is removed from the atmosphere by the new forest. With sustainability criteria we imply that biomass is sourced from areas without land use changes or land use competition issues.

Hydrogen (H_2) is an inherently carbon-free energy carrier that can be used as an alternative energy source. Hydrogen can be fed to fossil fuel fired furnaces with only minimal adaptations to the burner and fuel system. This is why the technologies using hydrogen can be considered as attractive for guiding the transition towards a carbon-neutral economy. With respect to new applications within industry, the main predicted uses of hydrogen are decarbonisation of high-temperature heat demand and feed for novel processes. However, the widespread use of hydrogen in energy-intensive industries would require major infrastructural investments by establishing hydrogen networks.

Today, the vast majority of hydrogen produced today is so-called 'grey' hydrogen, which is made by steam reforming of natural gas or naphtha or by gasification of oil or coal. The carbon atoms in the hydrocarbon feed are converted to CO_2 and released in the atmosphere, resulting in significant emissions. The hydrogen is called 'blue' in case (the majority of) these emissions are captured using CCS. Hydrogen can also be made from bio-based feedstocks (see above) or by electrolysis of water using renewable energy, resulting in 'green' hydrogen.

Only green and blue hydrogen can be regarded as part of the transition towards a carbon-neutral economy in 2050. Blue hydrogen production can be realised on the short term by retrofitting existing hydrogen plants with CCS. Hydrogen is currently mainly produced integrated in the ammonia production process and in separate hydrogen plants near refineries (CertifHy, 2015). Refineries have additional potential for blue hydrogen production, since the majority of CO_2 emissions from refineries is caused by combustion of refinery fuel gases in process furnaces (CONCAWE, 2011). These fuel gases can be fed to newly constructed hydrogen production plants fitted with CCS technology, thus eliminating the majority of CO_2 emissions from refining operations (H-vision, 2019). However, the economics of such plans still look poor. For example, blue hydrogen from Norwegian natural gas is expected to cost around 55 €/MWh in 2030 (CE Delft, Nuon, Gasunie, 2018) – a factor 2.5 higher than current average cost for energy in the energy-intensive industries. Green hydrogen requires large quantities of low-cost, low-carbon electricity. Green hydrogen from North African solar PV is expected to cost around 50 €/MWh in 2050 (Agora Energiewende, 2018).

The current price of grey hydrogen is a further limit to use hydrogen to process feed in refining and fertilizer production. However, production of hydrogen within the energy-intensive industries could also provide a niche market as significant demand could arise for home heating, mobility and support of the electricity system (FCH, 2019), (Hydrogen Council, 2017).

3.3.6. Technologies for Carbon Capture, Utilisation and Storage (CCUS)

CCUS describes the processes to capture CO_2 for either reuse (CCU) or permanent sequestration (CCS). The goal of CCU is to keep carbon in the cycle, reducing the need for virgin fossil feedstocks. The goal of CCS is to permanently remove the CO_2 from the atmosphere. The common part between CCU and CCS is the capture of CO_2, for which several mature technologies are available, such as precombustion capture, post combustion capture, in oxy-fuel combustion and direct air capture (see Annex A).

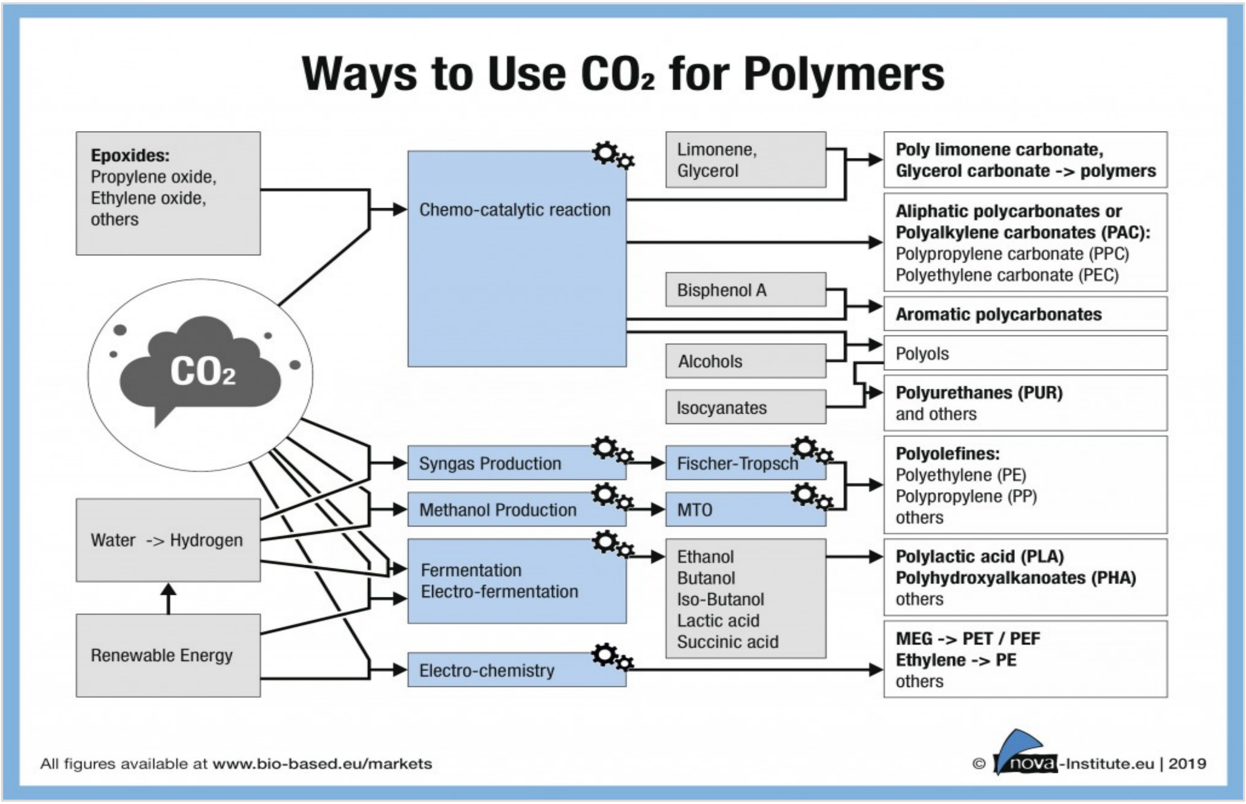
CCS is especially useful for those processes for which other routes are not available or too costly. Additionally, some processes produce CO_2 from a chemical reaction other than combustion, for example the reduction of steel in a blast furnace using cokes or the production of lime. This CO_2 emission is inherent to the chemical process itself and cannot be prevented unless the entire process or product is changed and hence needs to be captured. In other cases, CCS can be regarded as a fallback option in the transition towards a carbon-neutral economy. For CCS purposes, CO_2 can be sequestered by underground storage in empty oil and gas fields or aquifers.[18] Storage in both empty oil and gas fields and aquifers is technically mature, but currently only profitable if the CO_2 is used for enhanced oil and gas recovery.[19] Storage capacity available in Europe is not foreseen to be an issue until 2050, although this is not equally divided over all regions, leading to potential local constraints in available storage capacity (Budinis, Krevor, Mac Dowell, Brandon, & Hawkes, 2018).

The first major barrier for CCS is the cost, mainly caused by the high cost of the capture itself. For ammonia, a break-even point could exist for CO_2 costs of around €25/tCO_2 (as presently is being paid in the EU ETS). However, an important second hurdle is the lack of infrastructure. Finding a suitable reservoir, validating it and obtaining a storage permit are complex, time-consuming processes. Planning and building a pipeline is time and capital-intensive as well. A suitable reservoir is not available in each region, necessitating long distance transport of CO_2, where it is to be stressed that transport other than through pipelines is not acknowledged under current ETS rules.

CCU can be used in numerous different products, one study identified 130 different CCU products (EC, 2017). For a schematic overview of potential pathways of a CCU example of polymer production, see

Figure 7.

Figure 7: Schematic overview of potential pathways to use CO_2 for the production of polymers



Source: (Nova Institute, 2019).

[18] Alternatively, CO_2 can be stored by enhanced weathering of olivine bearing minerals, but this technology is not discussed further as it stores atmospheric CO_2 and as such is not relevant for industry (Strefler, Amann, Bauer, Kriegler, & Hartmann, 2018).

[19] To illustrate the maturity of the technology: the Norwegian Sleipner gas field has seen annual injections of around 1 Mton CO_2 since 1996 (Equinor, 2019).

In Annex A we have identified five potential promising areas of carbon utilisation by CCU:

- **Mineralisation** converts mineral oxides or silicates and CO_2 into mineral carbonates. The product can be used as aggregate in civil construction. CO_2 is permanently sequestered in the mineralisation process.
- **Methanol** can be produced by direct conversion of CO_2 and hydrogen into methanol. Methanol as a platform chemical can be further converted into olefins for polymer production (MTO), into gasoline (MTG), into dimethyl ether (DME), into methyl tert-butyl ether (MTBE) or used directly as fuel.
- **Polyurethanes** are made by reaction of isocynates with a polyol. Polyurethanes can be used as rigid foams in, among others, mattresses, car seats and shoes.
- **Reuse of steel off-gases,** instead of combustion in thermal power plants, it can displace fossil fuel and feeds. Both ArcelorMittal and TataSteel/Dow Chemicals have developed plans for, respectively, synthetic ethanol and naptha production.
- **Synfuels via Fischer-Tropsch** are produced from CO_2 and green hydrogen in the Fischer-Tropsch synthesis process. Large amounts of renewable electricity are required to produce the hydrogen via electrolysis (Concawe, 2017). Although the Fischer-Tropsch technology is mature, the potential for synthetic fuels is limited due to the large amounts of renewable electricity required and much higher prices compared to fossil fuels (Christensen & Petrenko, 2017).

The capture cost is not a significant barrier for CCU, as the cost of carbon is only a small percentage of the price of most CCU products (CE Delft, 2017). However, the cost of energy is more significant, especially for CCU routes that require large amounts of (green) hydrogen. The net avoided CO_2 of CCU routes is not immediately apparent and an LCA is required for each product route and application to verify the overall climate benefits. All of these routes, except the mineralisation route, depend on the use of renewable electricity or green hydrogen as well. There is a potential competition of the production of green hydrogen for CCU routes with other uses of renewable electricity.

3.3.7. Technologies dealing with process intensification (PI)

Process intensification is a design philosophy in chemical engineering that drastically decreases the size and hence cost of chemical equipment by thoroughly redesigning the equipment. This reduction is achieved by intensifying heat and mass transfer, applying new separation principles or combining functions conventionally performed by separate pieces of equipment into one (Stankiewicz & Moulijn, 2000). It is estimated that process intensification can offer an improvement of 20% in energy efficiency within the petrochemical sector around 2040 (Creative Energy, 2007). Similar achievements can be obtained in the iron and steel industry by using the Hisarna process.

The concept of process intensification has been around since the 1970's, but industry uptake is still limited to a number of niche applications. Bielenberg and Bryner mention the following factors for this slow adaptation:

- capital costs and reliability, availability and maintainability risks associated with implementing new processes;
- intensified, modular systems are very complex, no standard equipment and techniques yet exist;
- insufficient software, design tools, and data to develop intensified processes;

- challenges related to the technical, economic, and intellectual property of developing standardised design and manufacturing protocols for a complex new technology space at an early point in its technical and commercial development; and
- limited understanding of design and operation of PI technologies across a broad range of key industry sectors.

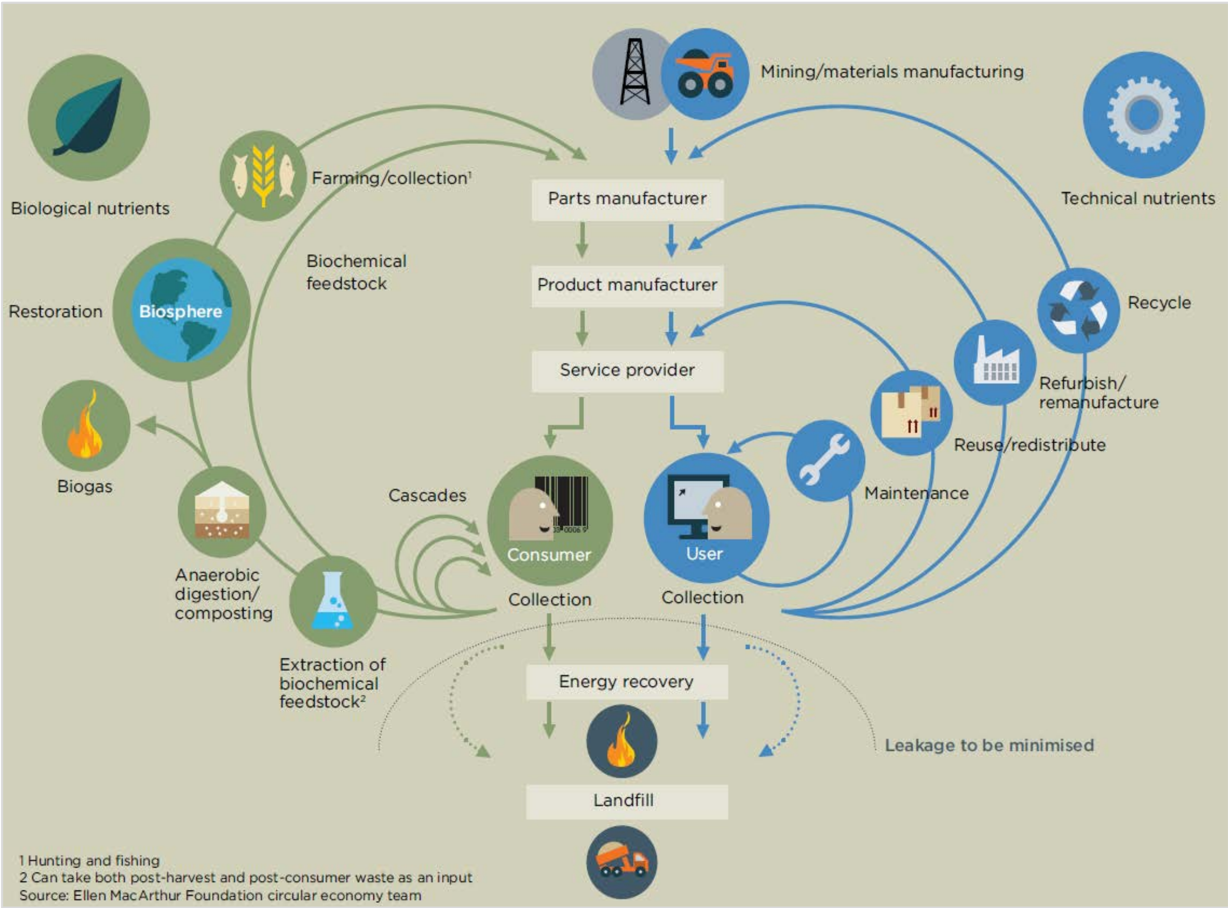
The development of new processes is key to limit the energy consumption of energy-intensive industries and to safeguard competitiveness in the long run.

3.3.8. Technologies concerning the circular economy

The whole transition towards a carbon-neutral economy can benefit from a similar development towards the circular economy. According to the Ellen McArthur Foundation, the circular economy is a systemic approach to economic development where through a regenerative design of products and processes a decoupling of economic growth from the consumption of finite resources is achieved.

A circular economy is created by using products as efficiently as possible and retaining maximum value when a product eventually breaks or reaches end of life. This means that refurbishment is preferable over recycling, reuse over refurbishment and maintenance over reuse. This preferential order is indicated in the figure by the length of the cycle: shorter cycles retain more value and should thus be applied before the longer cycles.

Figure 8: Graphical representation of the circular economy



Source: (Ellen MacArthur Foundation, 2013).

Transition towards a more circular economy has major benefits for the low-carbon economy:

1. Reduced environmental impact of resource extraction, production processes and waste disposal.
2. Optimised economic efficiency by retaining value.
3. Increased security of supply of materials through substitution of primary inputs by secondary inputs.
4. Lower depletion rate of finite supply of scarce materials.

However, the impact on the sectors under consideration in this report is partly indirect. In general, a larger share of primary materials, whether it is in the iron and steel sector, cement or chemical sectors would have to be substituted for secondary materials. Adaptation of the circular economy could lead to an emission reduction of up to 60% in industry 2050 (EC, 2018) by requiring less virgin material and reduced energy demand of the processes associated with the reduction strategies compared to primary manufacturing. The transition to a more circular economy is at least as much a societal and business model change as it is a technological change. Economy-wide changes are required as opposed to technologies such as electrification or CCS, which only require the adaptation of manufacturing equipment and additional infrastructure. While the shorter cycles in Figure **17** offer increased economic and environmental benefits over the longer cycles, their implementation is generally more challenging from a supply chain and consumer behaviour perspective.

While the adaptation of circular strategies generally represents a reduction in energy demand and emissions, this is not necessarily the case, especially if the process to reuse materials is energy-intensive. The positive impact of circular products should be confirmed by using standardised life cycle assessment (LCA) methodology. Some of the benefits in reducing emissions fall outside the energy-intensive industries (Scope 3 emission reductions[20]) and thus 'do not count' as emission reduction for the energy-intensive industries. These indirect emission reductions are direct emission reductions in other sectors and therefore there is always a potential for double counting of emission reductions.

3.4. Application of technologies in energy-intensive industries

3.4.1. Available technologies

All of the technologies identified in Section 3.3 can play a role in the energy-intensive industries under consideration in this study. Table 2 provides examples for every technology route in the energy-intensive industries.

[20] Scope 1 emissions are direct GHG emissions of the process itself. Scope 2 emissions are indirect emissions that were caused during production of the electricity that is being used in production. Scope 3 are indirect emissions that were caused during the production of all other materials, products and services that are used in production.

Table 2: Examples of available technologies for the energy-intensive industries

Sector	Circular economy	Electrification	CCUS	Hydrogen (H_2)	Biomass	Other process innovation
Iron and steel	More scrap recycling, replace by wood in construction	Electric Arc Furnace, Electrolysis of Iron Ore	Capture ready: ULCOS, HIsarna[21]. Steel2chemicals, Steelanol.	H_2-Direct Reduced Iron: HYBRIT, SALCOS, H2Future, etc.	Blast furnace on bio-cokes	HIsarna
Cement and Lime	Concrete recycling		CCUS on clinker oven, LEILAC, mineralisation	HT heat	Bio-fillers, biogas fired kiln	Low-carbon cement, CO_2 curing
Chemicals, polymers and fertilizers	Higher quality plastics recycling, naphtha from waste plastic, reduce fertilizer use	Cracker of the Future, Electric boiler	CCUS on SMR, Oxy-fuel + CCUS	H_2 from electrolyser, HT heat	Bio-based feed: MeOH, EtOH, bioBTX, H_2 from biogas	Catalytic ethylene cracker, novel separation technologies
Refineries	Recycled Carbon Fuels, reduction of demand by electric vehicles	Heat pumps, electric boiler	Synfuels, capture/CCUS on SMR	HT heat	Biofuels, bio-crude as input	Novel separation technologies

Source: Authors' own elaboration.

It should be noted, that many of these technologies, especially in the area of electrification, CCU and hydrogen assume the availability of large sources of renewable electricity. These technologies are thus dependent on the development in the electricity sector. On the other hand, energy efficiency, circular economy measures, process innovation measures and CCS often imply a direct reduction in the CO_2

[21] HIsarna is a new technology identified under the Ultra-Low CO_2 Steelmaking (ULCOS) programme of the EU. HIsarna is an evolution of the blast furnace process where powdered coal can directly be delivered to the reactor. The process delivers energy and CO_2 savings of > 20%. Almost pure CO_2 can be captured with minimal additions to the reactor.

emissions. As long as the electricity sector has not gained carbon neutrality, increasing electricity demand may, on the margin, because a delay in the closure of fossil fuel-based electricity generation and thereby not adding to climate neutrality of the economy.

3.4.2. Barriers to implementation

In the short term, low-carbon technologies are more expensive than their fossil counterparts mainly due to the cost of fuel. Moreover, investments in energy savings or CO_2 reduction do not offer the same return as other investments, for example capacity expansion, and investment in new installations is not competitive with the continued operation of fully depreciated assets.

In the longer term, many more transformative technologies are not yet ready for mass-market implementation. Most technologies also require new or upgraded infrastructure.

Business case and funding

The marginal cost of fossil technologies is in many instances lower than that of CO_2-neutral alternatives, even for new installations. This difference is even stronger when comparing continued operation of existing, depreciated assets with investment in new installations. In that case, both marginal and fixed costs are higher.

Investment decisions for new technologies face bias by cultural factors internal to organisations in cases where investment in new, more efficient installations is on paper competitive with operation of existing assets (ICF International, 2015). For example: energy saving may have low priority in an organisation and the proposed projects might focus on low risk, low return projects with minimal influence on the existing process. Such a focus on “business as usual” operations with minimal changes drives up the perceived risk and hence cost of new, more transforming investments while at the same time undervaluing any additional benefits of the new installation such as improved flexibility or reliability.

Infrastructure

New or strongly expanded infrastructure is required for electrification, production and distribution of hydrogen and reuse or storage of CO_2 in CCUS projects. Electrification, CCU and the production of hydrogen will require large amounts of additional electricity, requiring reinforcement of the electricity grid in general and the placement of additional transformers near industrial sites. Transportation by pipeline is the most efficient option for large amounts of hydrogen and CO_2, but most areas currently lack infrastructure for both gases, making development of new infrastructure a critical prerequisite for the successful deployment of CCUS and hydrogen.

R&D

Multiple technologies need additional R&D before market adaptation. The more advanced the technology, the less developed it generally is, but the higher the potential benefits. Some technologies or routes could benefit from efficiency improvements with additional R&D; others need further development before becoming feasible at all. As an example, the technology for electrification of existing steam demand is readily available, but a major portion of steam use for low and medium temperature can be replaced by much more efficient heat pumps, which require additional development. Electrification of high-temperature heat and process intensification generally employ more advanced technologies and are currently not market ready.

CO_2 reduction depends on external factors

Many technologies depend on the availability of low-carbon electricity in order to achieve a net reduction in CO_2 emission. Electrification, CCS, CCU and the production al require large amounts of electricity. This electricity should be available and should be low-carbon and low cost. Additional demand from industry can be significant and requires deployment of additional low-carbon generation capacity, renewable or otherwise.

Likewise, CO_2 emission reduction from CCU is not a given. Besides the high-energy requirements of some CCU routes, the duration of carbon sequestration is an important parameter for overall emission reduction and should be properly accounted for. CO_2 that is eternally sequestrated by carbonation of minerals has a higher value than short-term storage of CO_2 in for example carbonated beverages or synthetic fuels.

3.4.3. Alternatives routes

The technologies presented above are likely to play a major role in the transition towards a climate-neutral economy in 2050. However, we cannot afford to wait until 2045 to apply these technologies. In the meantime, also reductions of CO_2 have to be achieved. Natural gas and nuclear-based routes can provide an alternative. Natural gas-based routes can be interesting as transition technologies.

Natural gas

Natural gas has a roughly 40% lower carbon intensity than coal per unit of energy content. Substituting coal by natural gas can deliver major emission reductions in the short term, but does not lead to deep decarbonisation in the longer term. Many European countries have announced a phase out of coal between 2020 and 2035 (Beyond Coal, 2019). Given the ambition for climate neutrality in 2050, a subsequent natural gas phase out or mass adaptation of CCUS will have to take place after the coal phase out. This leaves only limited time for new investments in processes or fired units that use natural gas to recuperate their investment. Conversion to hydrogen in a later stage could offer the short-term climate benefits of natural gas while simultaneously retaining the possibility of deep decarbonisation towards 2050. Additionally, new-fired units could be installed as hybrids in markets with high penetration of variable renewable energy sources to allow flexible operation on electricity or natural gas, depending the prevailing electricity price.

In the Iron and Steel industry, natural gas can play a role in the transition phase by implementation of the Direct Reduced Iron / Electric Arc Furnace (DRI/EAF) production route. Iron ore is reduced in solid using natural gas and melted (with scrap) in an electric arc furnace. Investing in the DRI/EAF route based on natural gas would result in a ~40% CO_2 emission reduction compared to the Blast Furnace/ Basic Oxygen Furnace (BF/BOF) route. The DRI equipment can later be converted to use hydrogen from water electrolysis, resulting in emission reductions of over 80% (voestalpine AG, 2018).

Natural gas can also be used to make hydrogen in a conventional steam reforming process, which offers low emission energy with the addition of CCS. This so-called blue hydrogen is further discussed in Section A.5.

Nuclear energy

Current nuclear energy concepts rely on the splitting (fission) of atoms to generate heat, which can be further converted to electricity. Nuclear power plants are capital-intensive and have long construction times (WNA, 2017). Major overruns in both construction cost and duration are not uncommon; see for example Flamanville 3 (FR), Hinkley Point C (UK), Olkiluoto (FIN) and Vogtle 3 & 4 (USA) projects.

A decline of installed nuclear power is foreseen both for 2030 and 2050 due to retirement of Europe's aging nuclear fleet and insufficient addition of new installed capacity (IAEA, 2019).

Small Modular Reactors (SMR) are designed to address the challenges with conventional nuclear design. While a typical conventional nuclear plant is 1000 MW or more, SMRs are as small as 15 MW.

Standardisation of the design and shop-fabrication should lead to lower costs and shorter construction times (WNA, 2019). Although SMRs have undergone significant development, the concept is still mostly in the R&D phase, with only a few first-of-a-kind pilot installations currently under construction.

The idea of thorium reactors originated in the 1960's and various research reactors have operated since. Thorium is proliferation safe, there is a large supply of thorium and the radioactive waste decays quickly. Although much research has been done on thorium reactors, no commercial reactors have been built yet (WNA, 2017).

Certification and commercialisation of new nuclear reactor concepts takes years. After this stage, the lengthy planning and construction processes follow. Given the uncertainties and the time required for development, the feasibility of large scale SMR and thorium reactor deployments before 2050 is subject to discussion. If nuclear energy is to play a growing rather than a diminishing role in the decarbonisation of Europe, a major increase in projects is necessary.

3.5. Interpretation and conclusions

There are plenty of technologies available that can potentially guide Europe's energy-intensive industries towards carbon neutrality. The major hurdle however, currently, are related to costs. Both high upfront capital costs and higher operational costs provide an effective barrier towards uptake of these technologies. Often technologies provide carbon-neutral energy at a costs a factor 2 or 3 higher than from fossil fuels. This will be a major challenge for energy-intensive industries to overcome.

Table 3 provides a picture of the energy costs in 2017 (excluding feedstocks) for the identified energy-intensive sectors in relation to the production value (sales of the products) and gross operating surplus (as a measure of profitability).

Table 3: Estimated share of energy costs (excluding feedstocks) in 2017 in the EU27

	as % of sales price	as % of gross operating surplus
Refineries	2%	24%
Organic Chemicals	4%	64%
Fertilizers	4%	35%
Cement	5%	51%
Basic iron and steel	11%	79%

Source: Calculations based on Eurostat Structural Business Statistics. EU27 average based on data from 10 countries (Austria, Belgium, Germany, Italy, France (2016 data for refineries and cement), Greece, Hungary, Poland, Portugal, Spain). For refineries, for Italy and Germany, data based on CE Delft estimates of the share of coke production in sector 19 (oil refining and cokes production).

This table shows that if energy costs would double, cement would have to be sold at 5% higher prices to recuperate the higher costs. Alternatively, if these costs cannot be passed onto consumers, cement industry would see a fall of 51% in their gross operating surplus. Especially for basic iron and steel, the situation would become problematic if energy costs would double: either product prices would have to increase with 11%, or profits would fall with 79%. For fertilizers, refineries and organic chemicals these costs do not cover the costs of providing carbon-neutral feedstocks: it is likely that if these sectors were to provide carbon-neutral products, the costs could become up to a factor 2-3 higher. One should realise, however, that industry may still have 30 years to recuperate those costs.

Next to the higher costs, many of these technologies have to be embedded in a wider framework that is outside the scope of energy-intensive industries themselves but must be addressed in wider regulatory frameworks.

First of all, many of the technologies require investments in infrastructure: grid reinforcement of electricity networks, CO_2 pipelines and green hydrogen networks. Individual companies may not be able to realise efficient networks in this area and governments may have to step in to invest and allocate a fair price to the users of these networks while maintaining a business case for investment in carbon-neutral technologies.

Second, for technologies related to using biomass, the wider framework consists of the limited availability of large supplies of biomass of recently captured carbon that meets sustainability criteria. The use of biomass easily competes directly or indirectly with other land uses. Stringent regulatory rules would be required to determine which use of biomass is acceptable and which not. Our analysis suggested that use as feedstock's or fuels for which no alternatives are available (aviation/maritime) seem to be most promising.

Third, for technologies related to electrification, hydrogen and CCUS, the wider framework consists of the limited availability of large supplies of renewable energy. The renewable energy system must not only accommodate present demand, but also accommodate augmented demand from transport (electric vehicles). The question to what extent renewable energy generation can be enlarged to also cover demand from industry for carbon-neutral technology options. In addition, these routes would require substantial investments in infrastructure in electricity networks and hydrogen and CO_2 pipelines.

Other technologies, like energy savings or redesigned processes, do not have these drawbacks and should therefore be priority technologies. This will come back at the design of a technology roadmap in Chapter 5.

4. REVIEW OF EXISTING FINANCIAL INSTRUMENTS

4.1. Introduction

Chapter 3 provided the insight that additional costs are one of the main obstacles for energy-intensive industries (EII) in applying carbon-neutral or at least a less carbon-intensive production methods. There are additional CAPEX costs to be made. In addition, for many technologies, OPEX costs are higher than for the present fossil fuel-based production routes. Third, quality issues may impede application of low-carbon technologies.

Reduction of costs is central for a successful transition of the EII, and costs reduction preferably needs to occur sooner rather than later. Therefore, a relevant question is to what extent the present EU instruments are fit for purpose in

- Which financing solutions are available to accelerate the transition?
- Should this rely only on private finance?
- Through which smart and targeted solutions can public institutions and programmes help support the industry's transition, without running the risk of crowding out private investments or creating dependencies?

The overview will both contain an overview of carbon pricing instruments as funding mechanisms, although the main emphasis will be on funding mechanisms.

4.2. Price instruments

The EU ETS is the main European policy instrument through which emissions of CO_2 are being priced for the energy-intensive industries. Phase IV of the EU ETS that runs from 2020 to 2030 shows more ambition in reduction of CO_2 emissions compared to present. Yearly the share of allowances issued will be decreased by 2.2% from the average emission cap in Phase II of the EU ETS (2008-2012). In addition, the installation of the market stability reserve, and the withdrawal of the excess allowances through the cancellation mechanism, imply important updates compared to the present system.

Because of these changes, prices in the EU ETS have been increasing since 2017. For the future, market analysts expect that prices stabilise around the current €25/tCO_2. Afterwards, prices may increase because of growing scarcity but may also fall because more allowances become available from the increase in renewable energy generation. Analysts forecast price ranges between €15-35 by 2030 at the end of phase 4 with relatively more observations on the upper bound of this.[22] Indicatively this would imply that with an assumed price for an emission allowances of €30/tCO_2, the costs for complying to the EU ETS regulation by the nine energy-intensive sectors as identified in Section 0 would increase to around EUR 5 billion in 2030 if they would maintain their emission level of 2018.[23]

Although important, many critics have vowed concern about the lack of price stability in the EU ETS. Since 2008 prices have been falling considerably and only gaining momentum since 2018 (see Figure 9). This would result in companies demanding higher risk premiums for low-carbon investments. Although analysts expect that price stability will be increased with the introduction of the market stability reserve, the future EU ETS price development remains uncertain.

[22] See e.g. (ERCST et al., 2019).

[23] This is calculated as the average of verified emissions minus allocated emissions multiplied by the average emission price.

Figure 9: Price development spot market in the EU ETS, 2008-2020, in €/tCO_2 (current prices)

Source: SendeCO2.

In addition to the EU ETS, companies may also be taxed for energy in the Member States. Energy-intensive industries are large companies that have favourable rates of energy taxes in most European countries (OECD, 2018). Research (see e.g. PWC, 2018; Ecofys, 2017) has indicated that most countries have chosen to only comply to the minimum tariffs from the Energy Taxation Directive (2003/96/EC). These minimum tariffs do not differentiate towards CO_2 content of the fuels and are, on average, very low for business uses and use, in some cases (e.g. metallurgical and mineralogical industries) null-tariffs. Therefore, energy taxation currently does not provide a stimulus for the transition towards carbon neutrality, at least not at the European level.[24]

4.3. Funding and investment instruments

4.3.1. Existing instruments

In Europe, there are various funding and investment instruments available that can provide capital to energy-intensive industries. These include, amongst others:

- The European Fund for Strategic Investments (EFSI) and EFSI 2.0;
- Programme for Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME);
- European Structural and Investment Funds (ESIF);
- Horizon 2020;
- Just Transition Fund;
- Innovation Fund.

These funds are described in detail in Annex B. Table 4 provides a summary of each of these funds and puts them into context.

[24] In some countries, e.g. the Netherlands and France, CO_2 taxes for industry on top of the EU ETS price have been proposed or are under investigation.

Table 4: Overview of existing funding mechanisms for energy-intensive industries

	EFSI	COSME	ESIF	Horizon 2020	Just Transition Fund	Innovation Fund
Objective	Closing investment gap after financial crisis	Enhancing the competitiveness of European SMEs	Promoting economic, social and territorial cohesion	Supporting European research and innovation to ensure Europe produces world-class science, remove barriers to innovation and strengthen private and public research cooperation	Reduce emerging regional disparities caused by the transition towards a climate-neutral economy	Create financial incentives for next generation of technologies projects, boost growth and competitiveness, supporting low-carbon technologies in all Member States
Measures	Funding inter alia infrastructure, education, renewable energy and energy efficiency projects	Facilitating SMEs financing, access to markets, entrepreneurship and creating better framework conditions for competitiveness	Funding investments in research and innovation, digital technologies, sustainable management of natural resources, small businesses and supporting the low-carbon economy	Funding a research and innovation programme with a call for proposal mechanism	Investments in SMEs, R&I, deployment of technology and infrastructure, digitalisation, circular economy and job-search assistance and consultation	Funding highly innovative technologies and big flagship projects
Budget	EUR 16 billion guarantee by EU budget and EUR 5 billion provided by EIB (EFSI), additional EUR 10 billion guarantee by EU budget and EUR 2.5 billion provided by EIB (EFSI2.0) until 2020.	EUR 2.3 billion	EUR 461 billion	EUR 80 billion	EUR 7.5 billion	Up to EUR 10 billion depending on carbon price
Duration	2015-2020 (EFSI & EFSI2.0)	2014-2020	2014-2020	2014-2020	2021-2027	2020-2030

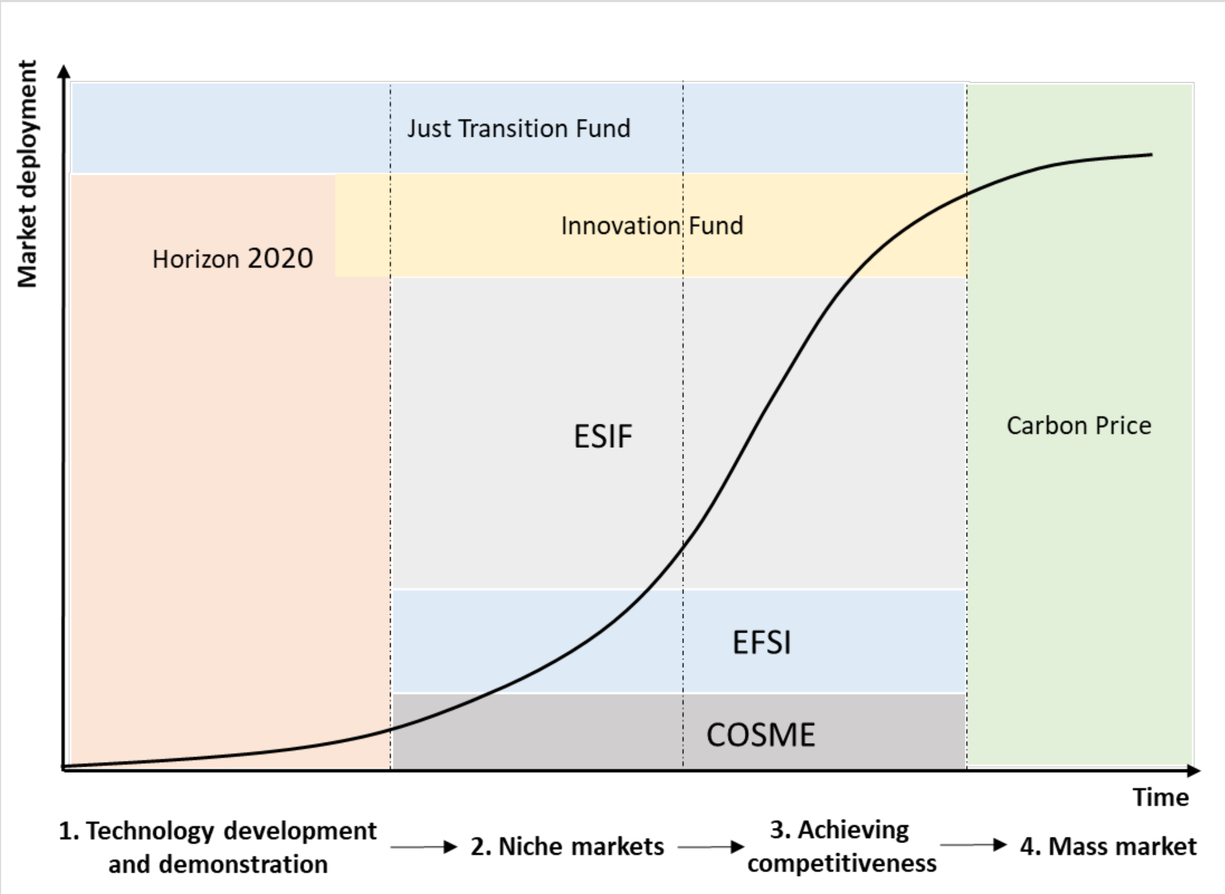
Source: European Commission and authors' own elaboration.

4.3.2. Analysis

The present funding mechanisms are targeting different uses in the technology cycle.

The figure below displays a generic technology development curve. The time axis displays the four subsequent stages of development from innovation to mass-market penetration. The y-axis represents the market deployment of a technology. This means, the later the stage of technology development the greater is its deployment in the market.

Figure 10: Overview of funding instruments and their area of application within the technology cycle



Source: Hood (2011), own classification of funding programmes.

Specific funding programmes focus on specific stages of this development. Although the described funding programmes apply to variety of sectors and technologies, there are certain programmatic attributes specific for each funding programme.

H2020 is the programme intended to support the beginning phase of technology development. With its clear purpose of funding European research, the funding programme can finance inter alia demonstration projects. The EFSI, on the other hand, already finances a big share of projects that have matured beyond the research and development phase. The funding programme and its management could be enhanced by focusing on projects and technologies, which already left the stage of development and are on the verge of gaining market shares but need further support.

The COSME's focus on supporting SMEs in gaining market shares, the programme's focus should lie on the development stage of niche markets and achieving competitiveness. However, the COSME budget is relatively small compared to the other programmes. One thinkable solution could be to shift the financing amount for smaller companies within the EFSI programme to the COSME programme. In this way, financial resources for SMEs could be bundled into one funding programme and strengthen the focus on SMEs as well as enabling easier access for companies. This could particularly benefit the development of new technologies and new business models, which are often developed by small and new firms.

The new just transition fund should focus on those areas, which specifically undergo structural changes and where whole industries are set to collapse (like coal mining industries, for instance). In order to support new economic development, it would be advisable to fund and accompany projects financially through the first three stages of technology development. This way it can be assured, that these areas will not become the new "left behind" regions and that new companies can evolve. At the same time, employment can be secured in those areas. However, the fund's budget is set to be relatively small. For decisive support and enabling the settlement of new companies with new technologies, the budget needs to be increased.

Overall, there is competition to some extend between the various EU funds.[25] To avoid financial overlap and to rectify the complexity of the overall EU funding scheme, it could be advisable to structure the programme's objectives in accordance to the technology development curve as displayed above.

The Innovation Fund's focus is a step in the right direction. It is planned to fund projects in the early development and demonstration stage, but does not cover basic research, which is the domain of the planned Horizon Europe programme. Furthermore, the fund is supposed to finance projects that are in either in the niche market phase or in the phase of achieving competitiveness and market penetration. In addition, the fund is set to explicitly address energy-intensive industries and their related low-carbon technology possibilities such as CCS and CCU. However, the fund's overall budget is relatively small – especially in comparison to the EFSI and the ESIF. The budget further relies on revenues from the auctioning of carbon allowances, which are uncertain to some extent.

Clearly, most of the programmes' funding scopes go beyond the simple financing of enhancing technological development. But in case of low-carbon technologies, a clear funding structure could lead to better resource allocation and better financial access for companies and research institutes. Further, most of the funds analysed above do not make explicit provisions for energy-intensive industries. Although funding is possible in most cases, a clear programmatic approach including EII and their related low-carbon technology development options would be preferable.

[25] European Commission (2017). Commission Staff Working Document. In-Depth Interim Evaluation of Horizon 2020. https://ec.europa.eu/research/evaluations/pdf/archive/h2020_evaluations/swd%282017%29220-in-depth-interim_evaluation-h2020.pdf

5. POLICY RECOMMENDATIONS

5.1. Introduction

With the European Green Deal, the EU sets itself the ambitious goal become the world's first climate-neutral continent by 2050. The European Parliament supports this ambition but calls for more stringent interim reduction targets. The European Commission has presented the European Industry Strategy in March 2020, outlining an industry policy based on the three drivers: greener, more circular and more digital.

The analysis in this study has shown that energy-intensive industries in Europe are competitive on world markets but that there is concern with respect to the costs of energy. Climate-related costs are likely to become a much more important determinant for competition in the short- to medium term. This also depends on whether other major economies in the world adopt more stringent climate policies: the more other major trading partners adopt comparable strategies and policies, the more level the playing field becomes. In the past, European energy-intensive industries have reacted to the rising labour costs by increasing labour productivity, thereby remaining competitive on the world market. A similar increase in energy and carbon productivity is needed to keep the European energy-intensive industries in pace with their non-EU competitors.

As this study and others have shown, numerous technologies are available that can help European energy-intensive industries progress towards carbon neutrality by 2050. The major hurdle however, currently, are the costs of these technologies. Both high upfront capital costs and higher operational costs provide an effective barrier towards uptake of these technologies. Some technologies that provide carbon-neutral energy do so at a cost that is a factor 2 or 3 higher than energy from fossil fuels. In addition, many of these technologies require substantial investments in infrastructure. This raises the question which share of the investments (and associated risks) should be covered by the energy-intensive industries, by other private investors and by the public budget.

Depending on the viewpoint and the timeframe, competitiveness is under threat both from a too rapid transformation – and from a too slow process. In the short run, and with the current set of climate policies in third countries, both costs and infrastructural provision present major challenges for the competitiveness of European energy-intensive industries. Yet with more and more countries adopting increasingly stringent climate policies in line with their Paris commitments, competitiveness will come to be determined also by the capacity to provide low-carbon products at competitive prices. Thus, while climate policy is perceived as an impediment to competitiveness in today's economy, it is also the key to competitiveness in tomorrow's economy.

Our analysis has shown that the current incentive structure is relatively weak. There are plenty of subsidies available for Research and Development of low-carbon technologies, however support instruments for the market uptake are not enough to incentivise investment at the necessary scale. Market forces will not solve this: the current price signal from the EU ETS is too low and too insecure to foster uptake of low-carbon technologies – significantly higher prices would achieve this, but at the same time would severely undermine the competitiveness of industries. Neither is there a sufficient market pull from consumers to provide an important stimulus. Therefore, a new regulatory framework should be considered in which both regulatory, subsidy and pricing instruments play an important role. Below we will in Section 5.2 first identify of which components such policy strategies should consist and then discuss in Section 5.3 relevant choices for policy makers in finding the right balance between carrot and sticks.

5.2. Policy instruments

Potential policy routes could be either based on one of the three main types of policy instruments:

1. Regulation and standards.
2. Pricing instruments.
3. Subsidy instruments.

Below we will identify useful components within each category of policy instruments.

5.2.1. Regulatory instruments and standardisation

Standard regulatory instruments can have an important role in the transition towards a carbon-neutral economy. Based on our analysis we foresee four special areas of these regulatory instruments:

- in the area of product policies;
- in the area of carbon accounting;
- in the area of biomass; and
- in the area of green public procurement.

Product policies can be important to stimulate the uptake of carbon-neutral product alternatives in consumer markets. Examples are the ban on single use plastics or the ban on the sale of incandescent light bulbs. Such regulation can drive the market penetration of market-ready low-carbon substitutes – and at the same time accelerate the market phase-out of incumbent products. They are typically applicable for products that readily available at (near) cost-competitive prices, and can accelerate their market penetration. Yet they can also be formulated as forward-looking standards that products will need to comply with in the future, thus setting a path for technological development (e.g. CO_2 standards for passenger cars).

Rules on carbon accounting are needed as a mean of standardisation. Especially in the field of circular economy and CCU there is a risk of double counting where both the producer and the user of the synthetic or recycled material would claim the CO_2 reduction. At the moment this is not uniformly laid out in EU regulation.

For biomass and all the routes that use renewable electricity (and renewable-based feedstock, as in hydrogen or CCU) an additional challenge is that competition for scarce resources may wipe out eventual climate benefits. Land use competition may imply that CO_2 from land-grown biomass may result in larger pressures to deforestation potentially causing a net increase in global CO_2 emissions. Competition for renewable electricity may imply that electricity used by energy-intensive industries competes with uses in e.g. transport (electrical vehicles). Such increased demand could slow down the decarbonisation of European electricity generation. Also here, proper rules on carbon accounting based on a systemic view would reduce the risk of unwanted outcomes from the transition of energy-intensive industries towards climate neutrality.

Finally, proper rules for accounting would be required to settle the issue of Scope 3 emission reductions where CO_2 reductions over the lifecycle of products are being realised. Scope 3.

For the use of biomass optimal valorisation could be required. An optimum use can be the use of biomass in applications that have the largest emission reduction, in applications where the highest economic value is realised or where no alternatives for decarbonisation are available. There is a possible tension between where the free market will use biomass and in which applications policy makers intend it to be used.

Green public procurement can become an important driver of creating niche markets and new business models. Every year, over 250,000 public authorities in the EU spend around 14% of GDP (around EUR 2 trillion per year) on the purchase of services, works and supplies. If these customers would demand that all products and services have to be carbon-neutral, this would trigger an impressive market demand for carbon-neutral products.

Typical problems related to this deal with measurement. Green public procurement has to set up *Product Category Rules* (PCRs) defining how the climate impact of a product over the lifetime has to be measured and taking into account in the procurement procedure. Within the work on the Product Environmental Footprint such PCRs are being developed.

Another problem is that green public procurement is not without costs. Adding carbon emissions as a criterion to procurement, for example through a shadow price for carbon emissions, means that companies will have to make additional costs to assure that there emissions are as low as possible. Moreover, it may limit competition if a few suppliers gain a competitive edge in providing low-carbon solutions.

Publicly supported lead markets for low-carbon products, e.g. commitment to use low-carbon steel, green cement or alternative bio-based materials (e.g. wood-based) in all construction of public buildings and infrastructure, could be an important stimulus for development of markets for such products.

5.2.2. Pricing instruments

The EU ETS continues to provide an important incentive for energy-intensive industries in the next decade, and allows them to build expectations for the future policy framework. However, the price signal from the EU ETS is not sufficient to bridge the cost gap for any of the decarbonisation technologies identified in Chapter 3. The CO_2 reduction achieved in the EU ETS so far mostly resulted from fuel switches (e.g. natural gas for coal, see ICF et al., 2016). Current price levels are not sufficient to incentivise investments in more radical techniques like CCS or process innovation. It is in this light interesting to investigate the casus of Hisarna where Tata Steel decided to apply a technique developed in Europe in an Indian steel plant. Obviously CO_2 pricing in the EU was not regarded as a decisive factor for investment.

This has to be changed in the coming decades. Research has indicated that an efficient CO_2 price must be much higher than currently observed in the EU ETS (see Section 4.2). In a project for DG Move, CE Delft (2019) provides an overview of the literature in this field and suggests that an efficient CO_2 price would be equivalent to EUR 60-189 in the short to medium term (up to 2030) with a central value of €100/tCO_2. The central value for 2050 is put at €269/tCO_2. Such prices would be representative of economy-wide carbon taxes that have to be installed if the European Union is to adhere to a global 2-degrees Celsius target.

It is clear that, in the short-to-medium run this would imply that the prices in the EU ETS would have to quadruple. The problem with this is that as long as the European EII have not achieved a higher carbon productivity, a higher CO_2 price is potentially translated into less competitiveness on world markets and thus the risk of losing market shares and investments.

Therefore, carbon pricing has to become smarter as to minimise the negative impacts on carbon leakage. Effectively, three different strategies can be considered:

1. To implement border tax adjustments alongside higher carbon prices in existing instruments like the EU ETS.
2. To implement consumption taxes based on carbon content alongside the existing carbon price signals from the EU ETS.

3. To implement alternative instruments as a carbon added tax instead of the EU ETS for energy-intensive industries.

Below these instruments are being described in more detail.

Route 1: Border Tax Adjustments next to the EU ETS

Border tax adjustments (BTAs) are import fees on goods coming from countries that have no carbon tax installed. An efficient system of border tax adjustments consist of a combination of export subsidies and import tariffs. Companies from EU countries which export to other countries get a refund for the costs of CO_2 allowances they incurred during production according to a benchmark, e.g. the CO_2 emitted to produce the product according to the best available technology. A charge is imposed on imported products from non-EU countries according to the same benchmark.

Border tax adjustments raise juridical questions. It has sometimes been argued that border tax adjustments are not permissible under GATT and WTO rules, because it is not possible to discriminate on the basis of production processes. Ismer and Neuhoff (2007) agree with this point in principle, but conclude that a border tax adjustment need not violate GATT and WTO rules provided that the export subsidy and import levies are not related to the actual CO_2 emissions in the production process, but to the CO_2 emissions in a best available technology. In this case, best available technology should be defined as minimal emissions per unit of output. Also Hillman (2013) concludes that BTAs can be justified under WTO rules.

A practical problem, however, is that under the EU ETS European industry favours protection from carbon leakage through free allocation of allowances. This would be an effective hindrance for installing Border Tax Adjustments as the WTO would judge that the free allocation scheme would discriminate against foreign competitors that have no free allowances to their possession. Therefore, the BTAs can no longer act as equalisation measures as the imported products would be taxed in excess of domestic rates Therefore, the EU ETS would have to abandon free allocation and embrace auctioning as the sole allocation mechanism.

If the EU ETS would be transformed towards an auctioning mechanism, foreign competitors could be taxed. However, it is important that the tax needs to be based on an equal basis (e.g. tonnes of steel), even if foreign competitors have a larger carbon content (Sakai & Barrett, 2016). Especially if the BTA is based on best available technology, rather than on actual emissions, it stands a fair chance of being held up against WTO rules

Border tax adjustments raise practical issues as well. A BTA may be relatively easy to implement if tax adjustments are only levied on products of ETS sectors. In some cases, these products are relatively homogenous (e.g. power, cement, chlorine, gasoline, etc.). However, such a design would only shift the impact on competitiveness to downstream sectors. An example can illustrate this point (CE Delft, 2008). Suppose that a BTA is in place for steel. In that case, EU steel producers would not be impacted by their inclusion in the EU ETS. After all, their exports are compensated for the costs associated with CO_2 emissions during production. And their sales in the EU market face competition from outside the EU which has been levied according to the CO_2 emitted during its production. Hence steel prices in the EU would rise. However, a steel using industry, such as car manufacturing, would be negatively impacted. The car manufacturing industry in the EU would need to buy steel for a higher price than a company located outside the EU. Consequently, it would see its competitive position deteriorate. This example shows that a proper border tax adjustment may be required for not only energy-intensive industries but a larger group of industries including cars and machinery. Border tax adjustments on such industries are probably more problematic in a WTO context.

Route 2: Consumption-based taxes next to the EU ETS

An alternative to border tax adjustments is the instalment of consumption-based taxes. In Climate Strategies (2016), it is investigated if the current pricing of the production of carbon-intensive materials can be supported by taxation of the consumption of carbon-intensive materials irrespective of where these materials are being produced. This would imply that energy-intensive industries within the EU no longer face unfair competition as not the production of e.g. steel is being taxed, but the consumption of steel. The report by Climate Strategies (2016) outlines how such schemes can be implemented.

The consumption-based tax (CBT) has the following elements (Climate Strategies, 2016):

- A liability is created upon the production of carbon-intensive commodities, e.g.at the time of the hot rolling of steel. This liability is then passed to products along the value chain.
- Firms can register with national authorities to receive, handle and dispatch products under duty suspension arrangements. Alternatively firms buy products free of liability.
- A product sold to a non-registered firm or to a consumer is released for consumption. The seller has to pay a charge into a national trust fund, to be used for climate action.
- The same liability to the charge is also created upon the import of carbon-intensive products and would be acquitted upon their export. A de minimis rule limits administrative effort.

The attractiveness of this proposal is that inclusion of consumption-based taxes builds on existing EU ETS structures. The coverage of installations included in the EU ETS is not altered.

Route 3: Alternative instruments based on carbon added taxation

CE Delft (2018) has investigated the possibility of a pricing instrument along the lifecycle of products that would eliminate the competitive disadvantage of energy-intensive industries from unilateral climate policies. This system is called External Cost Charge (ECC). The ECC could work as a voluntary scheme or be introduced as tax instrument. In the latter case, the scheme would work as a carbon added tax, similarly to the value added tax, but instead of taxing value in every step in the production chain, the scheme would tax added carbon.

The ECC would work as follows. Companies would have to keep track of the carbon emissions added in their link of the production chain, using a standardised calculation method to calculate the ECC to which they are subject. Companies would pay a charge on the added carbon, but, as with VAT, they could reclaim any ECC paid to suppliers of inputs. Firms and organisations that consider dedicated 'carbon accounts' too much work could opt to pay a standard charge pre-determined for each product group. At each link in the supply chain the firm in question would add their portion of the ECC, with the aggregate sum ultimately paid by the final consumers. The government could opt to compensate consumers for these price rises by lowering other taxes or by increasing subsidies on 'decarbonisation' measures.

The great advantage of the ECC is that it leaves international competitiveness unaffected as also importers have to pay for the scheme. Imagine the charge were levied in all EU member states. By allowing companies to reclaim the ECC on products exported from the EU and levying the same CEC on products imported to the EU as would have been paid by domestic producers, a level playing field is maintained, leaving competitiveness unchanged. For buyers of steel, for example, it would make no difference whether the steel was produced within the European Union or in Russia. This also implies that there will be no adverse impacts on competitiveness from carbon pricing.

An ECC would also incentivise European firms to lower the carbon content of their products so they can reduce the charge included in the price of their products and gain an edge over more polluting competitors.

5.2.3. Subsidy instruments

In the economic literature it is realised that only price instruments will not be effective in guiding a rapid transition towards a carbon-neutral economy (Acemoglu et al., 2012). Strong and stable carbon pricing policies are needed to improve the returns on investment in green infrastructure projects and to accelerate depreciation of existing fossil fuel assets. Removing direct and indirect fossil fuel subsidies is another core element of such a strategy.[26] However, providing subsidies would remain an important element of the transition for at least three areas:

R&D subsidies

Subsidies are required to further innovate existing and apply new technologies for technologies that have not yet entered the market. An important alignment challenge in the area of climate innovation arises from the fact that the benefits associated with the development and adoption of technologies cross borders (OECD, 2015). Therefore, innovation is most likely done at the European scale. A particular problem here is that politicians do not know in which directions innovation support should be channelled: should this be on process technologies, materials science or biotechnology.

From an economic perspective, the support should be technology-neutral so that the market itself can find out which technologies are most promising. However, this is difficult to realise in practice for innovation subsidies. Given the hazards associated with identifying promising technologies at an early stage of development, governments often support a “portfolio” of technologies, hedging their policy bets in the face of uncertainty (OECD, 2015).

Subsidies in infrastructure

A substantial part of the costs of the transition towards a carbon-neutral economy would come from investments in infrastructure, both for electricity grids and for pipelines of hydrogen and carbon. These investments are sometimes difficult to realise from private capital because infrastructure is often heavily regulated in countries (see also Section 5.3).

Another reason for investment in infrastructure is related to lock-in. The current infrastructure is fossil fuel-based with oil pipelines, gas networks, harbours, etc. This provides a lock-in competing against new networks. To overcome this hurdle, governments could consider financing the initial infrastructure and then asking users to pay for the services. As governments can lend capital more favourable than private parties, this could provide an important stimulus for the transition towards a low-carbon economy.

CAPEX/OPEX subsidies on top of the maximum affordable carbon price

The prime mechanism to drive investments towards low-carbon alternatives would be a CO_2 price signal. However, the current price signal has to be increased considerably for energy-intensive industries in order to play a role in the uptake of carbon-neutral technologies. Section 0 identified options how to increase the price signal without losing competitiveness and causing carbon leakage. However, if such proposals may not materialise, politicians should investigate the possibility of CAPEX and/or OPEX subsidies to cover the higher costs of low-carbon technologies.

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[26] OECD (2013) lists a total of 550 measures supporting coal, oil and gas production and use across the 34 OECD countries.

The main lesson to learn here is that such subsidies could be effective if they would form part of a tender system in which various industries must compete to provide the most reduction for the Euro of subsidies. Experiences in e.g. the Netherlands with this scheme on renewable energy subsidies provided that this has significantly reduced the cost of support (CE Delft, 2017).

5.3. Policy roadmaps

Policy roadmaps and technology roadmaps are to some extent interrelated. Ultimately, the selection of technologies should be an economic one, and not policy-based, with the most cost-effective and most competitive solution winning the day. However, for different reasons, that does not mean that the selection of technologies can be completely left to the market:

- markets provide insufficient long-term incentive and there is a high risk of continuing under a lock-in;
- technology development involves learning costs, economies of scale that bring the cost down over time – to have cost-competitive solutions tomorrow, we may need to invest in less promising options today;
- availability of infrastructure influences which technologies will win the day (technological, but also institutional arrangements);
- at the end of the day, we will probably need more than just one solution for energy-intensive industries, so one needs to roll out those that are cost-competitive already, but also need to bring down the cost for those that are still further away from cost-competitiveness, such as bio-based and CCU chemicals, electric furnaces and electrowinning of iron;
- some technologies require a change on the system level where public infra structure is essential for its introduction; and
- some technologies require synergy between different companies, and co-location on so-called Green field sites, for example CCU technologies or the cascaded use of biomass.

All this implies that politics has to play an active role in the development of support of technologies that are required from now up to 2050. Based on our study we foresee three different roadmaps:

- a technology roadmap for industry;
- an Investment roadmap for both the public and private sectors; and
- a roadmap towards competitive carbon costs.

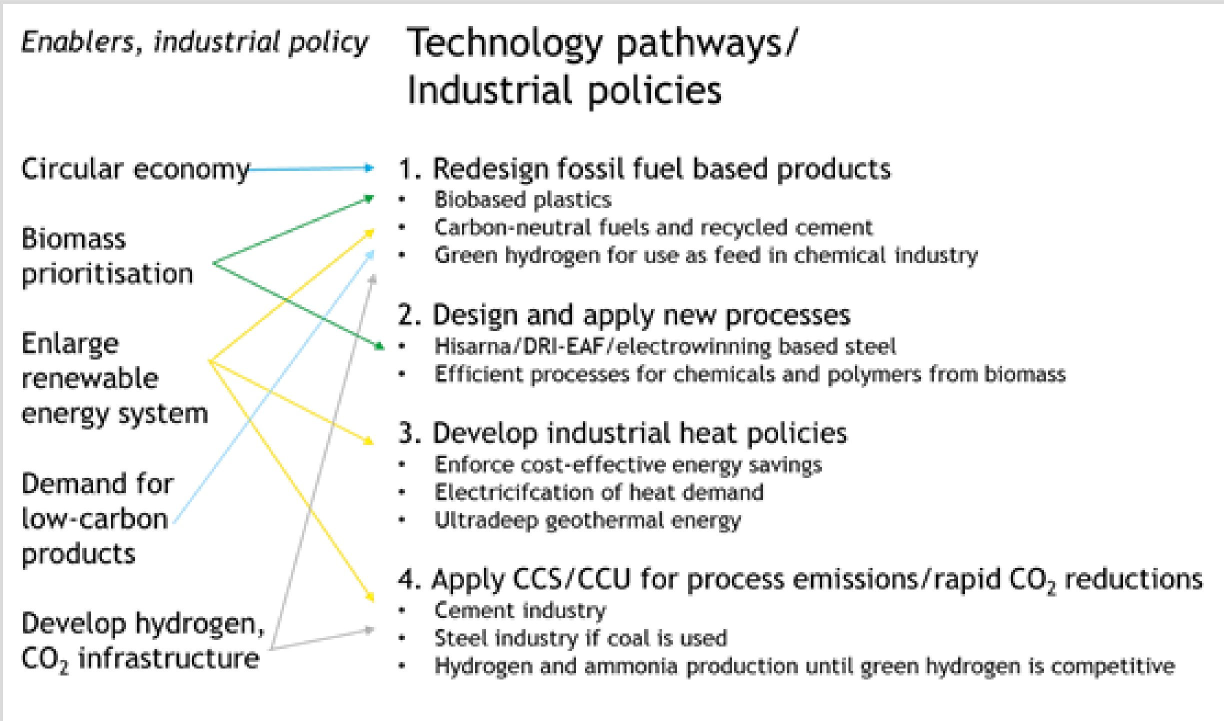
Below we will elaborate on these.

5.3.1. Technology roadmap for industry

Energy-intensive industries produce the materials necessary to fulfil our needs – and yet our utility does not derive from the materials themselves, but from the services provided by products, which in turn can use different materials. A home provides shelter – irrespective of whether it is constructed with traditional steel and concrete, with low-carbon or recycled steel and concrete, or with wood and other bio-based materials. Cars provide mobility – irrespective of what fuel they use and whether they use traditional or low-carbon steel, carbon fibre or aluminium. Packaging allows us to transport products – irrespective whether it involves traditional or bio-based plastics, paper or other bio-based or recycled materials. While the desired functions might stay the same, the EU's push for emission reduction of CO_2 and a circular economy will require a redesign of many products and services already in the next decade. Given the long investment cycles in energy-intensive industries, every major investment has to be a step towards a more competitive, circular and carbon-neutral industry at the same time.

A technology roadmap for industry can indicate the technological priorities for the coming years. A potential roadmap for the energy-intensive industries in the EU (based on existing sector roadmaps, complemented with relevant circular economy measures) is presented in Figure 11. This figure distinguishes certain enablers – societal developments that would enhance the technology roadmap and certain technology-related actions for industry.

Figure 11: Overview of the core elements of a technology roadmap for industry



Source: Authors' own elaboration.

The most important enablers are the growing demand for carbon-neutral products and the circular economy. The circular economy will reduce or alter demand for products in the energy-intensive industries. For example, car sharing will reduce the number of cars in circulation, and hence reduce consumption of steel. Concrete recycling will reduce demand for cement/clinker and increased use of organic fertilizers will reduce the demand for ammonia-based fertilizers.

At the same time, the circular economy agenda offers the opportunities for all energy-intensive sectors to rethink product design. This is the first element of the technology roadmap and would entail production of chemicals and polymers from biomass with minimal processing and the production of carbon-neutral (synthetic) fuels from CO_2 and green hydrogen with the highest chain efficiency. Where supply of biomass is sufficiently available, the chemical industry will have the possibility to switch from fossil feedstocks to renewable feedstocks: biomass and CCU using biogenic CO_2. The development of new materials that offer a maximum utilisation of the biomass molecular structure is a no-regret option that should be pursued in the short term due to the scarcity of the biomass supply. As there are limits to the amount of biomass that can be supplied from sustainable sources, available resources should be prioritised for use as bio-based feedstock, rather than for energetic uses as biofuels.

The prioritisation of biomass is an important enabler of the technology roadmap. The future production process of fertilizers can take place via carbon-neutral green ammonia and nitrogen and does not require much R&D, but mainly a lower price for green hydrogen. This would require large amounts of renewable electricity available at affordable prices. Therefore, enlarging the renewable electricity system to accommodate of future industrial demand is another important enabler.

Secondly, a drastic shift towards new carbon-neutral processes will be required. This implies that priority should be given to the (continued) development of among others HIsarna, hydrogen-based, and electrowinning for steel production. Rather than upgrading outdated processes by retrofitting CCS and electric heating, new and improved processes have innate advantages that cannot be matched by the older process. However, new investment should only use futureproof technology and also the existing production should be gradually but steadily converted. In the meantime, starting from today, the full economic potential of energy saving measures should be realised.

While retrofitting outdated processes with CCS is not recommended, CCS should be applied on all processes that have unpreventable CO_2 emissions, most prominently in the Cement and Lime sector and at waste incineration plants.[27] Climate neutrality cannot be achieved without CCS for those applications.[28] The alternative processes for steel, hydrogen and ammonia production will take over a decade to reach market maturity, so earlier carbon reductions can be achieved for these processes with CCS. Important and early greenhouse gas reductions can be realised by a swift rollout of CCS for those applications. The continued use of fossil fuels combined with CCS in a few select sectors gives some breathing room for the development of alternatives, which will take over the market in the longer term. Besides, it ensures that electricity usage by the energy-intensive industries does not get ahead of the development of renewable generation capacity.[29]

Finally, the fourth element of a technology roadmap is a strategy to reduce CO_2 emissions from heat. Heat demand in industry will have to be mostly electrified or use hydrogen or geothermal heat. Electrification is the most efficient option for low temperature heat using heat pumps. Heat pumps, mechanical vapour recompression and hybrid natural gas-electrode boilers are used for medium temperature heat and steam. The use of hydrogen for heat applications is far less efficient than direct electrification, but hydrogen can be stored and delivers high-temperature heat, so hydrogen can be a useful option for high-temperature heat in the longer term.

One should notice that this technology roadmap is not all-encompassing. Hydrogen as a feedstock is an essential ingredient for many processes in the energy-intensive industry of the future, except the Cement and Lime industry. However, this will only work if the hydrogen is itself green and low-carbon, i.e. if it is produced with surplus renewable electricity. Ever larger amounts of hydrogen are required towards 2050. The reduction of total cost of ownership of renewable energy generation, electrolysis equipment as well as the realisation of hydrogen networks are key development priorities here.

Table 5 gives an overview of specific technologies for the four energy-intensive sectors under scrutiny and puts them in a time-dimension. As is clear from the table, all technologies discussed in Chapter 3 have their own unique area of application, so all technologies benefit from further development both from R&D and learning by doing.

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[27] Due to the inherent loss of CO_2 during the process from the raw material itself, there is little potential for improvement of the core cement production process, but improvements in waste heat valorisation, carbon capture and reduction of clinker content are possible.

[28] As an alternative for CCS, mineralisation through CCU is a suitable alternative for locations without CO_2 storage possibilities close by.

[29] CCU routes for base chemicals and intermediates are usually more energy-intensive but can still play an important role to sequester carbon for long time periods in various materials.

Table 5: Technology roadmap for each sector, based on sector roadmaps and expert judgment. Measures stated with (CE) refer to circular economy techniques

Sector	2020	2030	2050
Iron and Steel	– CCS on blast furnace gas where possible – CCU on blast furnace gas for other plants – Mineralisation of slags – Increase scrap utilisation – (CE) Car sharing – (CE) Build with wood	– Replace blast furnace by HIsarna – DRI-EAF route	– Carbon-neutral steel: – BF/smelting reduction with CCS and/or bio cokes; or – DRI-EAF with green/blue hydrogen or biogas; or – Electrowinning with green electricity
Cement and Lime	– CCUS on kilns – Accelerated phase-out of non-PH-PC plants[30] – Curing with CO_2 – (CE) Build with wood – (CE) Concrete recycling	– Mineralisation of concrete waste before use as aggregate – (CE) Clinker substitution – (CE) Aggregates substitution – (CE) High strength concrete – (CE) Concrete recycling	Carbon-neutral concrete: – CCUS on cement and lime kilns
Chemicals and, Polymers	– Bio-based feeds for conventional plastics – Bio-based feeds for dedicated bio-based plastics – Chemical recycling of plastics, monostreams – Electric or hybrid boilers – Heat pumps, MVR's – (CE) Improved mechanical recycling – (CE) CCS on waste incineration plants to capture end of life emissions	– Chemical recycling, also of mixtures – CCU chemicals – Electric furnaces – Electric cracker	Carbon neutral chemicals: – Bio-based or CCU feed; and – Heat from electricity and/or geothermal; and – Capture of all process emissions
Fertilizers	– CCUS on hydrogen production – (CE) Increased use of organic fertilizer – (CE) Improved farming practices that require less fertilizer	– Production of fertilizer from green hydrogen	Carbon-neutral fertilizer: – Production from natural gas with full CO_2 capture; or – Production from green hydrogen
Refineries	– CCUS on merchant hydrogen plants – Electric or hybrid boilers – Heat pumps, MVR's – (CE) Car sharing – (CE) Accelerated electric vehicle adaptation	– Electric furnaces – Replace distillation by membrane processes or other energy efficient separation – (CE) Development of clean propulsion options for shipping and aviation	Carbon-neutral fuels: – Electric mobility – Green hydrogen – Synfuels from biogenic CO_2
All sectors	– Energy efficiency, full measurement of consumption at the sublevel.	– Closed mass- and energy balances – All pinches executed – Heat shared in networks	

Source: Authors' own elaboration.

[30] Plants that do not use a preheater and precalciner have substantially higher energy use.

One should realise that there are still major barriers to overcome before these technologies can be implemented. First, many of these technologies are likely to be considered only in the case of new facilities in, so called, Green Field facilities. This is problematic as the circular economy tends to reduce demand of energy-intensive industries rather than increase it. The realisation of new facilities based on new processes is capital-intensive and energy and operational cost savings might not be enough to offset the cost of the new Green Field facility. Existing facilities will only be replaced at the end of their life, which is after 2050 in many cases. An example of such a process is the HIsarna steel making of Tata, which offers relatively large energy savings, but will only slowly replace traditional blast furnaces without additional support.

In other cases, the capital expenses may be minor, but the operational cost of the new process can be much higher. This is the case for many applications of electrification.

Most combinations of the previous two barriers lead to the situation where the new process has higher production cost than the incumbent in addition to a large capital investment. An example of such a process is CCS, which offers no benefit to the producer but comes with significant capital and operating expenses which are currently neither covered by the ETS price nor by the customer.

As indicated in Section 0, many technologies require further development before reaching market maturity. Many bio-based and CCU processes for example have been proven at small scale, but have yet to be reach the technical maturity for widespread adaption. These processes require not only R&D, but also benefit from the effects of learning by doing through realisation of a pilot scale or small industrial demo plant. This also to experience setting up of chains and required synergies between companies providing the carbon source, the gas and power networks and the synthesis of final CCU products.

Lastly, infrastructure is a key requirement for hydrogen and CCUS. Without a publicly guided development strategy, heat, hydrogen and CO_2 networks will most likely not develop to the required extent solely by market forces and also should provide distinction between fossil and renewable resources on this infrastructure. This points at the necessity of an investment roadmap (see below).

5.3.2. Investment roadmap for public and private sectors

Over the coming months, governments across Europe will respond to the current economic crisis by launching stimulus packages to revive their economy and to restart economic development and growth. These measures will likely include measures to stimulate public and private investment. Therefore, they present a unique opportunity to accelerate investments needed for the transition of energy-intensive industries towards carbon neutrality. Likewise, they represent a risk if governments, under the impression of the crisis and in search of a quick fix, should chose to stimulate investments that cement the current structures in energy-intensive industries, and thus subsidise investments that could soon end as stranded assets. Much of the investment for transitioning to a climate-neutral economy will need to happen in the 2020's – which also means that investments supported under the announced wave of stimulus measures will need to be compatible with the transition to climate-neutrality.

A stimulus package that is geared at accelerating the transition would need to address the various investment needs outlined in this study. Yet, as the main goal of a stimulus package is to deliver immediate impacts for broad segments of the economy, investments in later phases of technology development are favourable. This would apply, for instance, to financial incentives for infrastructure investments, as well as investments into technologies that are close to market maturity, or have already achieved it.

Of particular interest are investments into the infrastructure for a climate-neutral economy, be they public, private or as a blend. While there are several areas where such investments will be necessary – from international high-speed rail to charging infrastructure for electric vehicles – there is one area that is of particular interest for energy-intensive industries: green hydrogen infrastructure. Green hydrogen is a promising element of several technological trajectories, yet to succeed economically, it requires infrastructure (in addition to plenty available renewable electricity).

A roll out of green hydrogen infrastructure would combine two important features: On the one hand, infrastructure investments have fast and substantial impact on the economy. They secure jobs in construction and planning and may lead to the creation of additional jobs. On the other hand, building this specific infrastructure is a necessary first step for a broad application of green hydrogen in the industry sector, which most areas in Europe currently still lack. Also, there is clear added value for supporting and coordinating such investments at the European level: as other energy products, green hydrogen would be traded in a pan-European network, capitalising on the differing endowments with renewable resources in different parts of Europe.

Next to the necessary pipeline network, the investment incentives could also relate to installations for the production and storage of green hydrogen. This would enable the faster deployment of carbon-neutral products from the EII and possibly give these sectors a comparative advantage in international markets.

Different tools are available to incentivise and support investments into low-carbon infrastructure, including for green hydrogen. This includes direct investment support, through co-payments, through tax breaks for investments or through accelerated depreciation rules. It could also include guarantees, through which the public would take over some of the risk of investments into carbon-neutral methods of production, as a measure to attract private investors. In this way, the burden of investment would not only lie on the shoulders of public finances but would distribute investment allocation between public and private investors.

In order to secure that investments are in fact distributed towards low-carbon technology options, a possible solution could also be an expansion and restructuring of the Innovation Fund. The main advantage of the Innovation Fund is its clear focus on EII. However, besides being of modest proportions, the fund is mainly fed by ETS auctioning revenues, which are under pressure in the light of the current crisis. Hence, equipping the fund with both direct liquidity and a substantial guarantee by the EU budget could enact private investments specifically addressing the transformation of Europe's energy-intensive industries.

5.3.3. Carbon pricing and costs roadmap

The investment roadmap will provide the necessary infrastructure for a carbon-neutral economy. However, infrastructure alone is not enough. The technology roadmap evidenced that both CAPEX and OPEX of carbon-neutral technologies are considerably higher than the present fossil fuel alternatives. Moreover, many facilities operating in the energy-intensive industries in the EU have been in operation for decades, implying that the capital costs have been fully depreciated. Carbon prices will have to rapidly increase in order to provide sufficient incentives for divestments of fossil fuel assets and make the technologies identified in this study attractive for replacement investments.

In the short to medium term, CO_2 prices have to increase to around €100/tCO_2 in order provide stimulation for technologies like CCS and provide stimulus to electrify current heat demand in industry. Such prices would also assure that the electricity is coming from renewable sources.

Such prices would have to be implemented at the EU level. However, it is likely that up to 2050, owing to the principle of "common but differentiated responsibilities", differences in carbon prices between

EU and non-western companies will persevere. Even though Chapter 2 identified that the EU ETS so far has not resulted in carbon leakage, there is ample evidence that such immunity may not hold for carbon prices of €100/tCO_2 without compensatory measures. High carbon prices will directly harm energy-intensive industries to an extent that production will fall and factories run the risk of being closed. This will lead to unwanted carbon leakage and social unrest.

The easy alternative route would be subsidise the cost differential between fossil fuel-based and carbon-neutral production. However, this is most likely a very costly route as this will entail significant transaction costs, open the floor for lobbying and result in misallocation of resources, making the transition far more costly (CE Delft, 2016). Moreover, it may lead to public concerns about worn-out governmental budgets and introduce political pressures to stop subsidy programs so that investors will demand additional risk premiums – costs that society will have to pay. Subsidies will also not change the situation that current fossil fuel assets remain profitable and will prevent replacement through new investments and organise political pressure for keeping those assets profitable. Therefore our assessment is that the subsidy route is unable to timely deliver the required emission reductions.

Therefore, there is not a real alternative to carbon pricing. A roadmap for carbon pricing would therefore consist of two elements:

- consider targeted mix of market-based support to bridge the cost gap, deliver price stability and provide recycling revenues to support innovation; and
- consider consumption-based pricing schemes including border tax adjustments.

Targeted mix of taxes and support

The main financial instruments will have to be a combination of carbon pricing schemes and subsidies. Carbon prices can provide price stability and certainty for investors, especially if they were to agree on a European scale to guarantee a level playing field in the single market. However, this does not imply that they have to be similar across sectors. The analysis in Chapter 3 showed that there may already be big differences between sectors in impacts for a unilateral doubling of overall energy costs. Carbon prices of €100/tCO_2 would double energy costs in the iron and steel and organic chemical sectors, more than triple in refineries and fertilizers and result in five time higher energy costs for the cement sector.[31] And result in even higher increases in refineries, fertilizers and cement. The differences between sectors and the differences in abilities of sectors to pass through part of the costs to consumers, would suggest that politicians should seek for targeted carbon pricing signals to industry. This would imply the following:

- Consider a dual tax system in which an average tax of around €25/tCO_2 is being combined with a marginal tax being a factor 4 higher only taxing emissions above a benchmark. For this marginal tax one could consider using the benchmarking system in the EU ETS as a basis for tax differentiation by only taxing emissions exceeding the pre-agreed benchmark. In order to do this, the benchmarks should be diminished themselves annually to reflect the necessary reductions in emissions. A marginal tax for industry on this basis has been proposed in the Netherlands (Dutch government, 2019).[32]
- Recycle the revenues of the average tax back to industry to support uptake and implementation of low-carbon technologies. The tax revenues should be earmarked for price support for industries in implementing low-carbon technologies. The main orientation of the

[31] Figures estimated using Eurostat statistics on purchase of energy products (sbs) and the EUTL verified emissions in 2017 for 10 countries (Austria, Belgium, France, Germany, Greece, Hungary, Italy, Poland, Portugal and Spain).

[32] The average cost component of the CO_2 tax to industry was considered but finally not included in the proposal.

subsidies should be OPEX subsidies so that the difference in operational costs between fossil fuel and carbon-neutral alternatives can be mitigated. This can be done through a contract for difference scheme where the difference between existing fossil fuel prices and the carbon-neutral activities is mitigated on an annual basis. In this way, low-carbon alternatives do not obtain a competitive disadvantage against the fossil fuel-based alternatives.

Consider consumption-based pricing schemes including border tax adjustments.

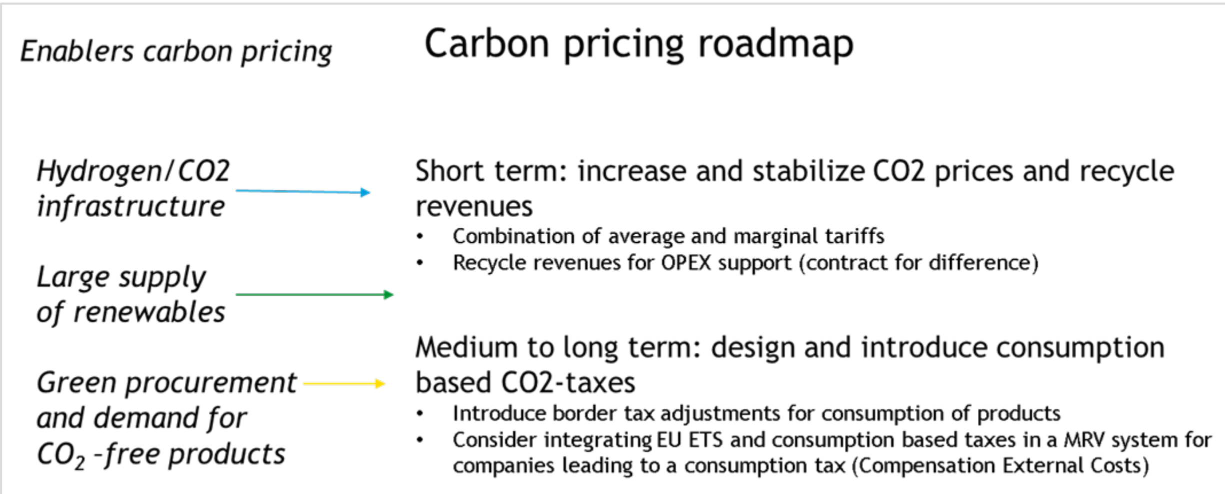
Higher carbon prices come at a cost of deteriorating competitiveness. Therefore higher carbon prices can only be implemented if they were to be connected with a border tax adjustment (BTA) that taxes imports in a similar way and exempts exports. The problem with border tax adjustments is that any 'exemption' to the tax base, as free allocation or exemptions, causes a complication in the BTA mechanism that is to be designed and runs the risk of not being compliant to WTO rules.

The alternative is to introduce higher carbon prices not through production-based taxes, but rather tax the CO_2 embodied in products. Recently, Climate Strategies (2016) and CE Delft (2019) have both proposed a consumption-based scheme for taxing embodied CO_2 in a product. If tariffs would not be fixed on a general benchmark but based on actual emissions, like in the Compensation External Costs (CEC), this could form an important stimulus for innovation and application of low-carbon technologies. However, such a scheme is complex and must be carefully designed as to minimise the chance of e.g. 'caroussel fraud' as in the VAT. The Climate Strategies proposal does not have this disadvantage but stimulates only material substitution at the level of the individual end consumer. In this way the scheme is not an alternative for production-based taxes as it does not stimulate lower CO_2 processes in energy-intensive industries directly.

Towards a policy roadmap

The roadmap is presented in Figure 12 and distinguishes a short-term and long-term element.

Figure 12: Carbon pricing roadmap



Source: Authors' own elaboration.

Both a CO_2/hydrogen infrastructure and a large supply of renewables can be considered as important enablers for carbon pricing as these are the necessity conditions for the carbon pricing scheme to work. Another important enabler is the demand from the market for CO_2-free products. Green procurement could play an important role.

In the short term the aim would be to increase and stabilise CO_2 prices and to recycle the revenues back to industry for OPEX support. In the long run one could consider introducing Border Tax Adjustments by switching carbon pricing from taxing emissions that arise during production (like in the EU ETS) towards taxing emissions during consumption. This may imply that BTAs can be more easily installed. The first move would be to tax a fixed amount of CO_2 tax per material or product which may stimulate material and product substitution. In a second step one could integrate the MRV obligation from the EU ETS into this scheme so that companies would have to factor in the real CO_2 emissions into the tax base. This could be administered in a system similar to the VAT.

6. CONCLUSIONS

This study has explored the way how the EU energy-intensive industries can transition to a climate-neutral economy while maintaining, and ideally improving, its global competitiveness. This research has investigated what technologies can support attaining the ambitious mid-century climate targets and how the uptake of these technologies can be facilitated through carbon pricing, subsidies and development of new business models.

Competitiveness of energy-intensive industries

Unequal carbon costs have long been considered as harming the competitiveness of European Energy-Intensive Industries (EEII), resulting in carbon leakage. So far, however, EEII have not shown signs of deteriorating competitiveness as a result of carbon costs. At the same time, nor have EEII yet obtained an increase in energy productivity that could absorb rising energy and carbon prices. Climate-related costs will therefore remain an important determinant for competition in the short to medium run. An increase in energy and carbon productivity can keep the European energy-intensive industries in pace with their non-EU competitors enjoying lower carbon prices. In the longer run, however, more and more countries will adhere to carbon pricing and competitiveness in a decarbonising global economy will primarily be determined by the capacity to deliver products with drastically reduced emissions. In this way, shielding EEIIs from higher carbon costs is only a short-term fix – and may risk leading them into a lock-in. A more long-term oriented competitiveness policy should instead aim to build up or extend technological leadership in the area of low-carbon industrial technologies.

CO_2 reduction technologies

There are plenty of technologies available that can potentially guide Europe's energy-intensive industries towards carbon neutrality. These technologies can be divided into those that reduce the CO_2 emissions of current processes (i.e. energy efficiency, carbon capture and storage), replace fossil fuels during production (i.e. electrification using renewable electricity, biomass, low-carbon hydrogen or other synthetic fuels) or develop new production pathways with a lower CO_2 footprint (carbon capture and utilisation; process intensification and circular economy). The major hurdles at present relate to costs, however. High upfront capital costs and higher operational costs both create an effective barrier to uptake of these technologies. The carbon-neutral energy provided by these technologies is often two or three times more expensive than fossil-sourced energy. Absorbing these costs into the business model will be a major challenge for energy-intensive industries to overcome.

In addition, many of these technologies need to be embedded in a wider framework that is outside the scope of the energy-intensive industries themselves and should be addressed via regulation in other areas, such as establishing rules for optimal cascading of biomass use and providing plenty of renewable electricity sources to satisfy growing demand in industry. In addition, many of the technologies require substantial investments in infrastructure for electricity and hydrogen networks and carbon pipelines.

Existing financial instruments

The present policy mix in the EU uses regulation, price instruments and subsidies. The EU ETS is the main EU policy instrument being used to put a price on CO_2 emissions for the energy-intensive industries. Phase IV of the EU ETS runs from 2020 to 2030 and has a larger annual decrease of available allowances. In addition, the installation of the market stability reserve and the withdrawal of the excess allowances through the cancellation mechanism imply important updates compared to the present system. Since 2017 the EU ETS carbon price has increased to €25/tCO_2 and it is projected to stabilise at around this level in the future even though the Corona Crisis may put a downward pressure on the prices.

In addition to the EU ETS, companies may also be taxed for energy in the Member States. Most countries have chosen to comply only with the minimum tariffs from the Energy Taxation Directive (2003/96/EC), which are very low for business uses, with in some cases even null-tariffs being applied., Energy taxation is not therefore currently providing any incentive for the transition towards carbon neutrality at the European level.

Subsidies and funding instruments are available for energy-intensive industries. These include, amongst others:

- **Horizon 2020 (H2020)** – Supports beginning phase of technology development, including demonstration projects.
- **The European Fund for Strategic Investments (EFSI) and EFSI 2.0** – Finances projects that are beyond the R&D phase. Could be enhanced by focusing on projects and technologies that have left the R&D stage and are on the verge of gaining market share but need further support.
- **Programme for Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME)** – Focuses on supporting SMEs in gaining market shares; the programme's focus should lie on the development stage of niche markets and achieving competitiveness. By shifting the financing amount for smaller companies within the EFSI programme to the COSME programme, financial resources for SMEs could be bundled into one funding programme and the focus on SMEs strengthened, as well as enabling easier access for companies.
- **European Structural and Investment Funds (ESIF)**.
- **Just Transition Fund** – Targets areas that are specifically undergoing structural changes and where entire industries are set to collapse (e.g. coal mining). It would be advisable to fund and financially support technology development projects with a view to improving competitiveness, so these areas will not become the new "left behind" regions and new companies can emerge that secure continued employment. For decisive support and enabling the establishment of new companies with new technologies, the modest budget needs to be increased.
- **Innovation Fund** – Intended to fund projects in the early development and demonstration stage and to finance projects that are in either in the niche market phase or in the phase of achieving competitiveness and market penetration. In addition, the fund is set to explicitly address energy-intensive industries and their related low-carbon technology options such as CCS and CCU. However, the fund's overall budget is relatively small and relies on uncertain revenues from the auctioning of carbon allowances.

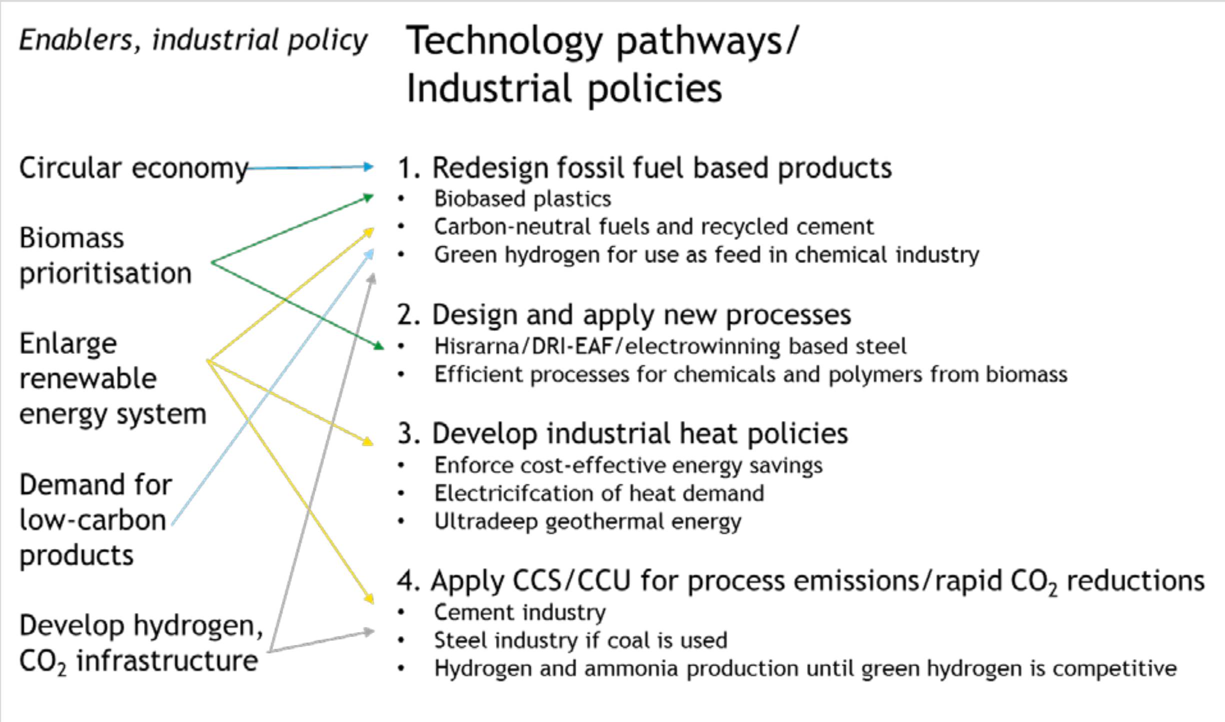
Overall, there is to some extent competition between the various EU funds. To avoid financial overlap and to rectify the complexity of the overall EU funding scheme, it could be advisable to structure the programme's objectives in accordance to the various stages of technology development.

Policy recommendations

The present instruments are not up to the task of guiding the transition towards a low-carbon economy. Carbon prices in the EU ETS are too low to provide sufficient incentive for uptake of low-carbon technologies in line with a path towards carbon neutrality in 2050. Carbon prices also need to rise to accelerate depreciation and dismantling of existing fossil fuel assets. Existing subsidies have small budgets, implying that only certain sectors will receive subsidies, with others missing out, hampering a smooth transition towards carbon neutrality.

A technology roadmap for industry can guide politics in designing effective subsidy schemes. In our technology roadmap we have distinguished "enablers" – societal developments that are crucial for the feasibility of the transition towards a carbon-neutral economy and "technology pathways" that are essential for the EEII.

Figure 13: Enablers and technology pathways



Source: Authors' own elaboration.

The most important enablers are the **growing demand for carbon-neutral products** and the **circular economy**. The circular economy will reduce or alter demand for products in the energy-intensive industries. For example, car sharing will reduce the number of cars in circulation, and hence reduce consumption of steel. Concrete recycling will reduce demand for cement/clinker, and increased use of organic fertilizers will reduce demand for ammonia-based fertilizers.

At the same time, the circular economy agenda creates an opportunities for all energy-intensive sectors to **rethink product design**. This is the first pathway in our technology roadmap and would entail production of chemicals and polymers from biomass, production of carbon-neutral fuels and recycled cement, and production of green hydrogen. This implies that almost all products within the EEII need to be redesigned with lifecycle carbon neutrality in mind.

The second pathway implies **a redesign of the processes** used in EEIIs. This implies that priority should be given to the (continued) development of among others HIsarna, hydrogen-based and electrowinning for steel production. Rather than upgrading outdated processes by retrofitting CCS and electric heating, new and improved processes have innate advantages that cannot be matched by the older process.

The third element of a technology roadmap is a strategy to **reduce CO_2 emissions from heat**. Heat demand in industry will have to be mostly electrified or use hydrogen or geothermal heat. Electrification is the most efficient option for low temperature heat using heat pumps. Heat pumps, mechanical vapour recompression and hybrid natural gas-electrode boilers are used for medium temperature heat and steam. The use of hydrogen for heat applications is far less efficient than direct electrification, but hydrogen can be stored and delivers high-temperature heat, so hydrogen can be a useful option for high-temperature heat in the longer term.

The last pathway is for those processes where emissions cannot be changed via one of the other methods. As retrofitting outdated processes with CCS is not recommended, **CCS/CCU** should be applied to all processes that have unpreventable CO_2 emissions, most prominently in the Cement and Lime sector and at waste incineration plants. Here, climate neutrality cannot be achieved without CCS. To some extent, CCS may also be an option for steel, hydrogen and ammonia production, where technologies may take over a decade to reach market maturity; this would thus provide a means of achieving earlier carbon cuts. This would be the most logical for facilities near CO_2 storage locations or pipelines.

This development needs to be accompanied by an acceleration of existing carbon pricing and subsidy schemes. **Investment support** is especially important for investments in the infrastructure for a climate-neutral economy, be they public, private or a blend. For their transition towards a carbon-neutral economy, EEIIs need new infrastructure (e.g. reinforcement of electricity networks, hydrogen networks and CO_2 pipelines to storage fields). Such infrastructure is often beyond the scope of individual companies and therefore needs to be accompanied by government support.

However, without substantially **higher carbon prices**, such investments run the risk of not being fully utilised. Carbon prices should be near €100/tCO_2 in the short to medium term, increasing to over €250/tCO_2 in 2050. Higher carbon prices come at the cost of deteriorating competitiveness, though, so can only be implemented if accompanied by a border tax adjustment (BTA) that taxes imports similarly and exempts exports. The problem with BTAs is that any "exemption" to the tax base, as free allocation or actual exemption, causes a complication in the BTA mechanism that is to be designed and runs the risk of not being compliant with WTO rules.

The alternative is to introduce higher carbon prices not through production-based taxes, but rather by taxing the CO_2 embodied in products. Such schemes affect the choices made by consumers, forcing them to take carbon costs into account. Especially if the scheme can be linked to actual measurement of the CO_2 emissions from individual production units, as in a recent proposal for a carbon added tax type of instrument (the External Costs Charge), this could provide an important stimulus for innovation and application of low-carbon technologies. However, such schemes tend to become complex and must be carefully designed.

Both a CO_2/hydrogen infrastructure and a large supply of renewables can be deemed important enablers for carbon pricing, as these are necessary conditions for the carbon pricing scheme to work. Another important enabler is market for zero-carbon products. Green procurement can also play an important role.

In the short term the aim would be to increase and stabilise CO_2 prices and to recycle the revenues back to industry for OPEX support. In the long run one could consider introducing Border Tax Adjustments by switching carbon pricing from taxing emissions arising during production (as in the EU ETS) to taxing emissions during consumption. This may make installation of BTAs easier. The first move would be to levy a fixed CO_2 tax per material or product, which may stimulate material and product substitution. In a second step one could integrate the MRV obligation from the EU ETS into this scheme, so that companies would have to factor the real CO_2 emissions into the tax base. This could be administered in a system similar to the VAT.

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ANNEX A. EXTENSIVE OVERVIEW OF TECHNOLOGIES

A.1. Technologies related to energy efficiency

Energy efficiency is often termed the "first fuel": the fuel that is not required due to reduced demand. Energy efficiency means producing the same products with less energy. The focus is on measures that do not radically change the production process itself, but rather optimize the energy use by reducing losses. Examples of energy efficiency measures are better insulation, reuse of waste heat, the use of LED lighting and more efficient electrical drives.

Because using energy is a cost to industry, energy efficiency in industry has already resulted in energy savings of around 40% per unit of product (EEA, 2019). There is a remaining technical potential for estimated additional savings of 15-25% in 2050 using current technologies (ICF International, 2015) (McKinsey, 2018). The economic potential is substantially smaller: only around 5% reduction in 2030 and 10% in 2050 is estimated to have a simple payback time of less than five years (ICF International, 2015).

At present, the main drivers to apply energy efficiency measures are related to growth and competitiveness (ICF International, 2015). This implies that in practice investments in energy efficiency compete with other projects that achieve the same goals. A lack of access to funding (Eurofer, 2013) leads to limited capital availability which may drive up the hurdle rate of all projects.

Because energy efficiency projects are competing with other expansive investments, the required rate of return is often high. The high required return on investment is clear from the significant difference between the technical and economic potentials for energy efficiency measures. In addition to this, there are often overlooked internal factors within companies that lead to a further increase of the required return, causing a diversion between the perspectives of those outside and those within companies (ICF International, 2015). In practice, a simple payback time of three years is already considered not profitable within some companies.

A.2. Technologies dealing with electrification

Electricity is an incredibly versatile power source that can drive many processes, from heating and cooling to chemical separation and electrochemistry. As electricity will become increasingly decarbonised towards 2050, there is a growing potential for emission reduction in industry by switching from fossil fuels and feedstocks towards electricity. The use of electricity often offers large efficiency benefits as well, for example in the application of heat pumps for low temperature heat. Additionally, electrification of industry could help balance electricity grids by offering flexibility to grid operators. This section will focus on the use of electricity for heat production and in electrically driven processes.

The importance of the decarbonisation of heat supply was highlighted in Section 2.2. Furnaces, steam and hot water and space heating have a major share in emissions in EU industry. Several commercially available technologies can be implemented to substitute fossil fuels for heat demand:

- **Electrode boilers** apply AC current to water, turning it into steam with nearly 100% efficiency. Additional benefits include low maintenance, no minimum load and an unrivalled response time. Electrode boilers supply saturated steam but can be equipped with an electric superheater to match the temperature of existing fossil fuel fired boilers. A hybrid system can be installed by installing an electrode boiler alongside an existing fossil fuel fired boiler. Electrode boilers are mature technology that is already widely applied in some sectors (Parat

Halvorsen, 2020), (Vapec, 2020), although penetration in energy-intensive industries is still minimal because of the comparatively high cost of electricity.

- **Electrical resistance heating** applies resistors to convert electrical current into heat with 100% efficiency. Resistance heating can be used to produce hot water, steam or thermal oil. Alternatively, heaters can be placed directly in the process, eliminating the need for heat exchangers. This reduces capital cost and increases the efficiency of the overall heating process. Resistance heating stems from the 19th century and is a mature technology with many applications. The use in energy-intensive industry is still limited because of the higher cost of electricity compared to fossil fuels.
- **Heat pumps** use electricity to drive a mechanical vapour compression cycle. This technology is much more efficient than the technologies above as electricity is used to displace heat rather than to create it. The ratio of usable heat produced versus the electricity consumption is expressed by the coefficient of performance (COP), which can range from 2 to > 5 (A2EP, 2017). The COP decreases with increasing temperature lift, which is the temperature difference between the waste heat and the produced heat. Single stage heat pumps deliver heat up to 100°C. The uptake in energy-intensive industries is limited because most energy is used at higher temperature levels, requiring further development (Heat Roadmap Europe, 2017).
- **Steam recompression** reuses low pressure steam that is normally condensed or vented. Excess low pressure steam can be recycled by compression up to process pressure with a conventional centrifugal compressor. Compared to venting or condensing, a COP of up to 10 is achievable in practical applications. Steam recompression is a mature technology with a largely untapped potential.
- **Electric arc furnaces** pass an electric arc through the material to be heated. The dominant application is the melting of metal in steelmaking. This material is either scrap metal or direct reduced iron.

Electrification of the steel industry

European steel plants mainly use the Blast Furnace - Basic Oxygen Furnace (BF-BOF) route. Iron ore is layered with cokes from coal in a blast furnace, where the carbon from the cokes reduces the iron ore to pig iron. Excess carbon is subsequently removed by treating the liquid steel with oxygen. Since coal is used to reduce the iron ore, the BF-BOF route has a large environmental impact. An alternative is the already mature Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) route. Iron ore is reduced to iron by reduction with natural gas in solid state. The hot product is molten and further treated in an electric arc furnace. In case a carbon-neutral reduction gas is used, such as green hydrogen, the steelmaking process is largely carbon-neutral and fuelled by renewable electricity in the DRI-EAF route. Hydrogen reduction is not yet proven at industrial scale and is currently more expensive than the BF-BOF route. Scrap can be added in the EAF for reuse. Scrap is often contaminated with copper, which is detrimental to the strength of the final steel. Without the addition of scrap, steel quality of the DRI-EAF route is comparable to primary steel from BF-BOF and can be used for example in the automotive industry. A further – fully electric alternative is electrowinning, which is still under development. Iron ore is reduced to iron in an electrolysis cell, requiring only electricity.

Other technologies such as induction heating, plasma heating, infrared drying and microwave drying have limited application in the industries under consideration and hence will not be discussed here.

Using a combination of the listed technologies, the entire steam demand of industry can be electrified (Schüwer & Schneider, 2018). On the other hand, industrial scale high-temperature furnaces such as used in the cement industry still need further development. Besides providing heat, electricity can also be used to drive certain processes. In electrochemical reactions, electricity is the driving force. Examples of widely applied electrified processes are the melting of scrap steel in an electric arc furnace, the production of chlorine and caustic soda by electrolysis of brine and the production of aluminium by electrolysis of aluminium oxide. A wide range of processes can potentially be electrified by the application of electrochemical processes. Some production pathways are already proven but could be scaled up further, many other require significant R&D efforts to reach commercial application and yet other production routes might not even be known currently. The vast majority of industrial processes can eventually be electrified, so that molecules are only required as feedstock and not as fuel.

The main barrier for the immediate deployment of most electrification technologies is economical (TNO, ECN, 2016). The average electricity price is higher than the cost of fossil fuels in all markets. For example, natural gas costs around 20 €/MWh wholesale in 2018, compared to around 50 €/MWh for electricity (EC, 2019). One should notice that this is not a problem for all applications: flexible technologies can be employed for fewer hours and highly efficient technologies can be profitable even when electricity is not cheaper than fossil fuels. Besides the higher OPEX, an investment is required of 150-190 k€/MW for an electric boiler up to 3.5-5 M€/MW for a furnace (DNV-GL, 2018) (Berenschot et. al., 2017). The combination of the current electricity and CO_2 markets and the required capex investments to convert equipment from fossil fuel fired to electric prevents investments in electrification in most cases. Investment in new installations is in general not competitive with continued operation of written-off existing installations (Eurofer, 2013). Uncertainty of electricity, fossil fuel and CO_2 prices and policies adds to this effect. The additional cost for selected production routes is indicated in Table 6.

Table 6: Estimated cost of electrification routes for three core products

Product	Production route	Cost of avoided CO_2 [€/t CO_2]	Product price increase [%]
Steel	Hydrogen direct reduction @ 40-60€/MWhe	18-57	6-18%
Cement	Electric furnace with CCS @ 40-60€/MWhe	66-89	84-115%
Plastics	Electric cracking and end-of-life CCS	113	33%

Source: Adapted from (Material Economics, 2019).

In case enough low-price and low-carbon electricity were available, infrastructural challenges await. Large industrial sites have a high energy demand. Replacing fossil fuels by electricity could lead to additional electricity demand of 100 MW to over 1 GW for a single large site. The current infrastructure was never designed with this demand and will need significant reinforcement. The cost of these reinforcements will need to be carefully allocated in order not to significantly deteriorate the business case for electrification.

The business case of electrification is worse on paper than in practice because benefits of electrification are often undervalued and drawbacks overstated. Electrification can for example lead to better process controllability, product quality and lower maintenance requirements, but these aspects are rarely factored into the business case if they are not the primary driver for electrification. By contrast, the reliability of electrified processes is often underrated because of a lack of experience with electrified processes.

Lastly, many electrification technologies require (sometimes significant) additional R&D and market experience to become mature.

A.3. Technologies for deep geothermal energy

Geothermal energy uses the ground as a heat source, either to generate electricity or to use the heat as is. This report will focus on the use of geothermal energy as process heat in industry.

Heat is extracted from the earth by pumping up ground water, using a heat exchanger to heat a process and returning the cooled water to the ground. The deeper the well, the higher the temperature of the water. The depth required for a certain temperature varies greatly with the structure of the ground. An example well could yield 60-80℃ at a depth of 2,000 meters, 120-130℃ at 4,000 meters and 175-200℃ at 6,000 meters (EBN, 2018). With a suitable underground, temperatures of 250℃ can be reached. Although these temperatures are too low for the iron & steel and cement sectors, both the chemical industry and refining have significant demand for temperatures of up to 250℃ (McKinsey, 2018), (Heat Roadmap Europe, 2017).

Few studies are done on the potential of geothermal heat in Europe and most focus on electricity production or district heating. The electricity produced can serve as a lower bound for the potential in 2050, since electricity can be converted to heat with a 100% efficiency. The electricity potential is estimated by one studie at 9 EJ/y (van Wees, Boxem, Angelino, & Dumas, 2013) and by another study as 15 EJ/y (Limberger, 2018). This is roughly the same order of magnitude as the entire energy demand of the sectors under consideration. The efficiency of electricity generation is usually only 8-16% of the extracted heat (Boxem, Veldkamp, & van Wees, 2016). This means that the potential will be able to cover the heat demand of industry many times over if all of the extracted heat is used directly as heat instead of converted into electricity with a low efficiency.

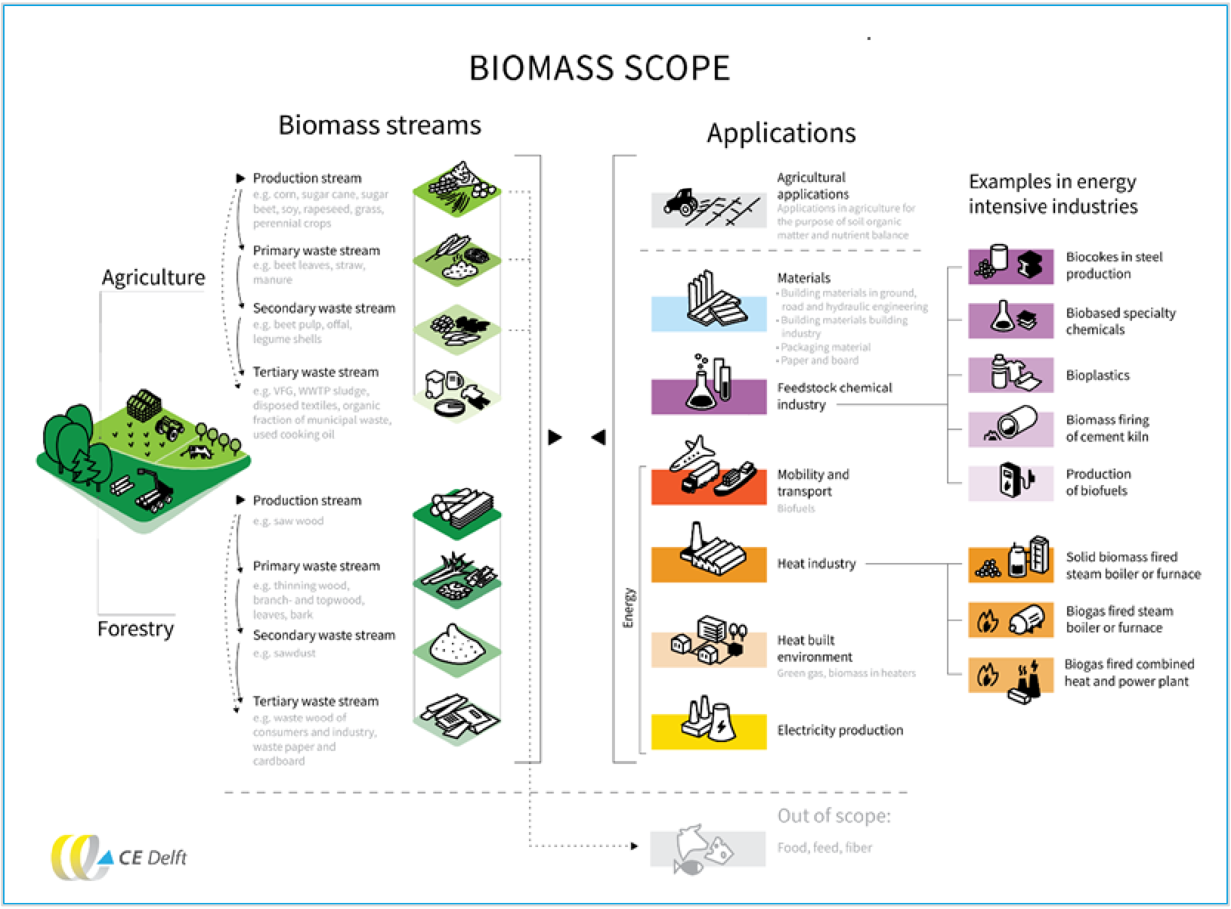
There are few existing projects for deep geothermal energy. Significant development is necessary before deep geothermal energy will be available for industry on a large scale. Because heat can be transported for at most a few kilometres with acceptable losses, development of a well is tied to the location where the heat will be used. While the general composition of the substructure might be more or less known, detailed research is necessary for each location. Geothermal projects are CAPEX intense and have low OPEX (EC, 2016). Financing cost is high because of the many risks associated primarily with the early stages of development of a geothermal project: potential risk of denial of a permit, a dry well, presence of oil and gas, earth quakes during development, contractor bankruptcy and many others.

With current estimated costs of low-temperature geothermal projects around 60 €/MWh (ETIP-DG, 2019), (ultra)deep geothermal has to come a long way before becoming competitive with fossil fuels.

A.4. Technologies for the use of biomass

Biomass is the umbrella term for all hydrocarbon materials derived from nature, with the exception of fossil sources. Biomass is sourced from agriculture, forestry and aquatic environments and comprises primary, secondary and tertiary waste streams in addition to the production stream, see Figure 14.

Figure 14: Biomass streams and applications



Source: authors' own elaboration.

The applications of biomass in industry are as diverse as its sources, but can roughly be divided in three categories: bio-based products, chemicals and energy uses. After discussion of some general considerations with regards to biomass, these three applications will be discussed in that order.

The carbon content of biomass consists of atmospheric CO_2 sequestered in plant matter. The combustion of biomass is often seen as climate-neutral since no overall increase in atmospheric CO_2 occurs recently absorbed CO_2 is re-release into the atmosphere through combustion of biomass. However, this critically hinges on the claim of 'recently absorbed'. Biomass does not lead to lower CO_2 emissions when mature trees or even primeval forest is used, since the carbon was absorbed a long time ago. In these cases it takes decades before the released CO_2 is reabsorbed by the newly planted trees.

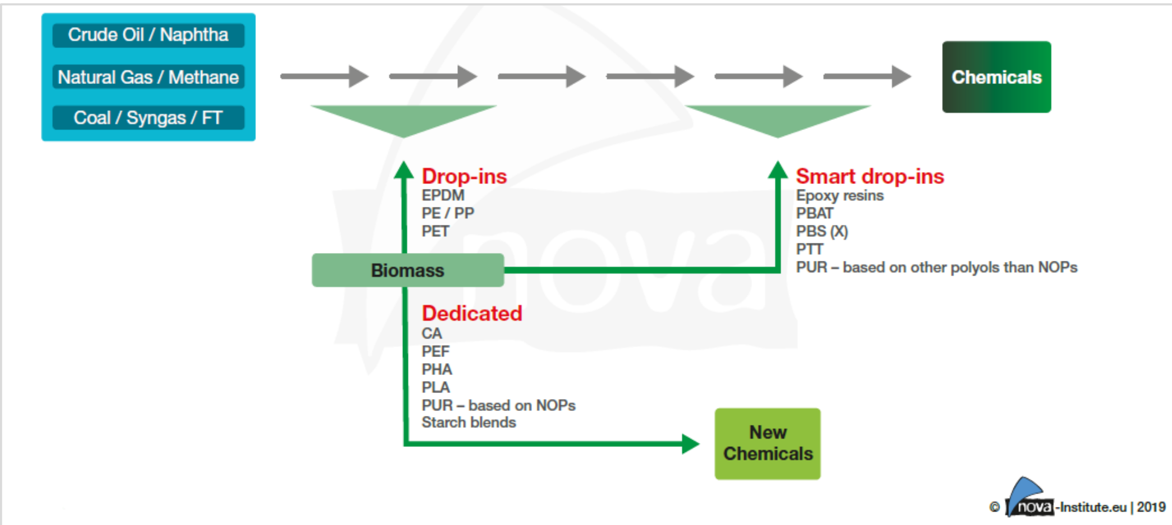
Biomass could completely replace the current fossil energy carriers and feedstocks, given a sufficient supply. The availability of biomass that meets the criterion of 'recently absorbed' is however limited. Various studies estimating the potential of biomass have been performed with a wide range of results. The presented potentials are highly dependent on the assumptions made with regards to future land use for food, animal feed and fibre, as well as the applied sustainability criteria. As a minimum, most studies apply the 'food, feed and fibre first' principle, which excludes land use for biomass on lands required to meet demand in these applications. Global biomass availability is estimated to be < 100 EJ/y with a high level of agreement among different sources, up to > 300 EJ/y with a low level of agreement (Creutzig et al., 2015). It should be recognised that this availability may in practice imply accelerated decay of natural habitats having adverse impacts on biodiversity through direct land use and increasingly through land use competition (Immerzeel, Verweij, van der Hilst, & Faaij, 2014).

Although the current sustainable biomass supply is small, there is an unidentified latent potential of biomass (waste) streams, including the biogenic part of municipal waste. Realisation of this potential will increase the potential emission reduction of biomass applications and is a no-regret measure as long as care is taken to adhere to strict sustainability criteria. Given the limited supply of sustainably sourced biomass, it makes sense to use biomass in high value applications first: the cascading of biomass. As an example, wood could first be used and reused in construction, then used as feed for other bio-based products, which can finally be turned into liquid fuels at the end of their life. Cascading can be based on maximisation of economic value of the applications, maximisation of greenhouse gas reduction or where no alternatives for decarbonisation are available. There is a possible tension between where the free market will use biomass and in which applications policy makers intend it to be used.

Bio-based products conserve the macrostructure of the biomass in the final product. Examples of well-established uses are wood, paper, natural fibres in clothing and straw roofing. An example of a potential future use with a requirement for further R&D is lignin as binder in asphalt, replacing petrochemical bitumen.

Bio-based chemicals extract or produce specific molecules from biomass. Various approaches are available, from less efficient processes yielding generally applicable products to more efficient processes that yield specific products. In general, the closer the product molecule resembles the molecules in the feedstock, the more efficient the process can be (DECHEMA, 2018). This is displayed in Figure 15. As a start, 'drop-in' chemicals can be produced: bio-based chemicals that are identical to existing petrochemical platform chemicals. Drop-in chemicals can be fed to an existing chemical process without adaptations, though the production chain is lengthy and inefficient, with limited CO_2 reduction potential. One step up in efficiency are so-called 'smart drop-ins', which more closely resemble the final product. The most efficient use of biomass is the production of dedicated bio-based chemicals that do not have a petrochemical counterpart and that closely resemble the feed. With an optimal process design, only limited processing is required, resulting in large CO_2 reduction potentials.

Figure 15: Schematic differentiation of pathways of drop-in, smart drop-in and dedicated bio-based chemicals



Source: (Nova Institute, 2019), used with permission.

Biomass can be converted to energy through combustion, with or without pre-processing. Biomass can be combusted in solid form for process heat. Biomass use for energy purposes amounted to around 1,350 TWh/y in 2016 in the EU (EC, 2019). Examples of use in industry are biomass fired boilers, cement furnaces fired with biomass or municipal waste and the potential use of bio cokes in primary steelmaking. The combination of biomass for energy applications, replanting of biomass and CCS (BECCS) leads to a net removal of CO_2 from the atmosphere, resulting in negative emissions.

Gasification or anaerobic digestion produces biogas, which can be purified into biomethane. At the end of 2017, Europe had almost 18,000 biogas plants, producing 65 TWh/y of electricity and 19 TWh/y of biomethane (EBA, 2018). Biogas installations often convert the biogas locally into electricity and heat with a CHP installation, rather than feeding the biogas into the grid. Alternatively, carbon-neutral hydrogen can be produced from biogas. Biogas, biomethane and hydrogen can be further processed into liquid fuels and chemicals.

Liquid fuels can be produced from biomass directly by (hydro)pyrolysis or in multiple steps by Fischer-Tropsch synthesis of syngas from biomass gasification, with pyrolysis having a notably higher yield and lower energy use. The production of liquid fuels could be said to have a higher value than combustion of biomass for heat, since the bio-based liquid fuels can be used in sectors where there are limited alternatives, such as aviation and international shipping. A high demand for liquid fuels well into the future, healthy margins and mandatory renewable energy targets for liquid fuels under the RED II regulation predict a strong demand for biomass from the fuels sector.

Energy and heating applications of biomass are well-established, but bio-based products and chemicals still undergo significant development. Production routes that fully valorise the molecular structure of biomass offer larger economical and sustainability benefits than general purpose approaches, but need more R&D to become mature. Bio-based production routes are commonly more expensive than their fossil counterparts. Bio-based plastics are generally up to twice as expensive as fossil plastics on a weight basis, although specific properties of bioplastics may reduce the amount of material required in some applications. The price difference is highly dependent on the type of plastic as well as oil and sugar prices (van den Oever, Molenveld, van der Zee, & Bos, 2017). While bio-based approaches have a large range of applications, the availability of bio-based feedstocks is limited. The applied sustainability criteria and the resulting availability are subject to societal discussions.

A.5. Technologies concerning the production and use of hydrogen

Hydrogen (H_2) is an inherently carbon-free energy carrier. Hydrogen is the most abundant element in the universe, but does not occur on earth as a pure substance. Unlike oil and gas, hydrogen has to be produced from other molecules in a chemical process. The vast majority of hydrogen produced today is so-called ‘grey’ hydrogen, which is made by steam reforming of natural gas or naphtha or by gasification of oil or coal. The carbon atoms in the hydrocarbon feed are converted to CO_2 and released in the atmosphere, resulting in significant emissions. The hydrogen is called ‘blue’ when (the majority of) the emissions are captured using CCS. Hydrogen can also be made from bio-based feedstocks (see Section A.4) or by electrolysis of water using renewable energy, resulting in ‘green’ hydrogen. Only green and blue hydrogen can be part of a transition towards climate neutrality. Blue hydrogen production can be realised on the short term by retrofitting existing hydrogen plants with CCS. Hydrogen is currently mainly produced integrated in the ammonia production process and in separate hydrogen plants near refineries (CertifHy, 2015). Refineries have additional potential for blue hydrogen production, since the majority of CO_2 emissions from refineries is caused by combustion of refinery fuel gases in process furnaces (CONCAWE, 2011). These fuel gases can be fed to newly constructed hydrogen production plants fitted with CCS technology, thus eliminating the majority of CO_2 emissions from refining operations (H-vision, 2019).

Hydrogen produced by electrolysis of water is a quickly growing production route, although the volumes produced are still very small. An overall emission reduction compared to blue or grey production routes is only realised if low-carbon electricity is used. This means that ideally the electrolysers should only be operated if there is an abundance of electricity produced by renewable sources so that on the margin the use of the electricity does not imply an increase in fossil fuels elsewhere.[33] The currently high capital costs of electrolysers prevents this type of operation, since a high utilisation factor is necessary to recuperate the investment. This highlight the two major prerequisites for the production of meaningful amounts of green hydrogen by electrolysis of water: the need for an abundant supply of low-carbon electricity at lower prices than natural gas and a cost reduction of the electrolysis equipment.

Over half of the EU's current energy consumption derives from imports (Eurostat, 2019). Similar to the current import of petroleum products, hydrogen might be imported in the future from countries with exceptional solar, wind or hydropower conditions. The hydrogen can be transported as a liquid, or converted to another molecule such as methane, methanol, ammonia or methyl cyclohexane (MCH).

Industry consumes over 90% of the hydrogen produced today, mostly as feed for chemical processes (CertifHy, 2015). The production of ammonia (NH_3) from hydrogen and nitrogen is responsible for 63% of the industrial consumption. A further 30% is consumed in refineries to desulpherise and upgrade fuels. Hydrogen is generally generated on-site or supplied by a high pressure pipeline with a number of large suppliers and consumers connected to it.

The use of hydrogen for the production of ammonia and the upgrading of fuels will persist into the future. With respect to new applications within industry, the main predicted uses of hydrogen are decarbonisation of high-temperature heat demand and feed for novel processes. As pointed out in Section A.2 on electrification, the technology to electrify high-temperature heat generally requires further development. By contrast, hydrogen can be fed to fossil fuel fired furnaces with only minimal adaptations to the burner and fuel system. The use of hydrogen for the production of chemicals and liquid fuels will be discussed in Section A.6 on CCUS. An important new application for hydrogen can be found in the iron and steel sector, in the technology of direct reduced iron. Hydrogen is used to reduce iron ore in solid state, as an alternative to currently wider employed blast furnace route.

Although this report is concerned with the European industry, it is useful to highlight the potential future demand in other sectors. Significant demand could arise for home heating, mobility and support of the electricity system (FCH, 2019), (Hydrogen Council, 2017). The allocation of low-carbon hydrogen to each of these sectors will depend on the willingness to pay, which is generally higher for private consumers than for a globally competing commodity industry.

New future hydrogen demand will have to use blue or green hydrogen in order to make a contribution towards the reduction of CO_2 emissions. The major challenge for the uptake of hydrogen in industry will be the production of sufficient quantities of low-carbon hydrogen at competitive prices. For use as high-temperature heat source, the price should fall below the price of natural gas including CO_2 levies. For use as process feed, the price should fall below the price of grey hydrogen. Blue hydrogen from Norwegian natural gas is expected to cost around 55 €/MWh in 2030 (CE Delft, Nuon, Gasunie, 2018), whereas green hydrogen from North African solar PV is expected to cost around 50 €/MWh in 2050 (Agora Energiewende, 2018). The current price of hydrogen limits its application to process feed, mainly in refining and fertilizer production. Virtually all hydrogen produced is grey hydrogen. Major price drops of blue and green hydrogen or price hikes of their fossil alternatives are necessary for this to change.

[33] This criterion is also satisfied if the electricity is being produced by additional units that are not connected to the grid.

Whatever the source, adaptation of hydrogen by industry requires major infrastructural investments. All sources require a hydrogen network to be realised. In addition, fossil fuel and CO_2 pipelines are required for large scale blue hydrogen generation. Green hydrogen requires large quantities of low-cost, low-carbon electricity. Hydrogen import requires the development of hydrogen terminals. CO_2 and hydrogen networks are absent in many industrial areas and hence need to be realised. While large scale production of green hydrogen will usually require electricity grid upgrades, it can also be used to eliminate the need for grid upgrades by colocation of the electrolysis equipment with renewable energy production. A global hydrogen market is in its very infancy and needs production, shipping and loading/unloading capacity.

A.6. Technologies for Carbon Capture, Utilisation and Storage (CCUS)

CCUS describes the processes to capture CO_2 for either reuse (CCU) or permanent sequestration (CCS). The goal of CCU is to keep carbon in the cycle, reducing the need for virgin fossil feedstocks. CCS is a necessary technology to eliminate emissions that cannot be abated by other technologies, such as process emissions in the cement sector. The combination of CCUS and biomass (BECCS) offers the possibility for negative emissions, which are necessary to offset emissions that cannot be prevented.

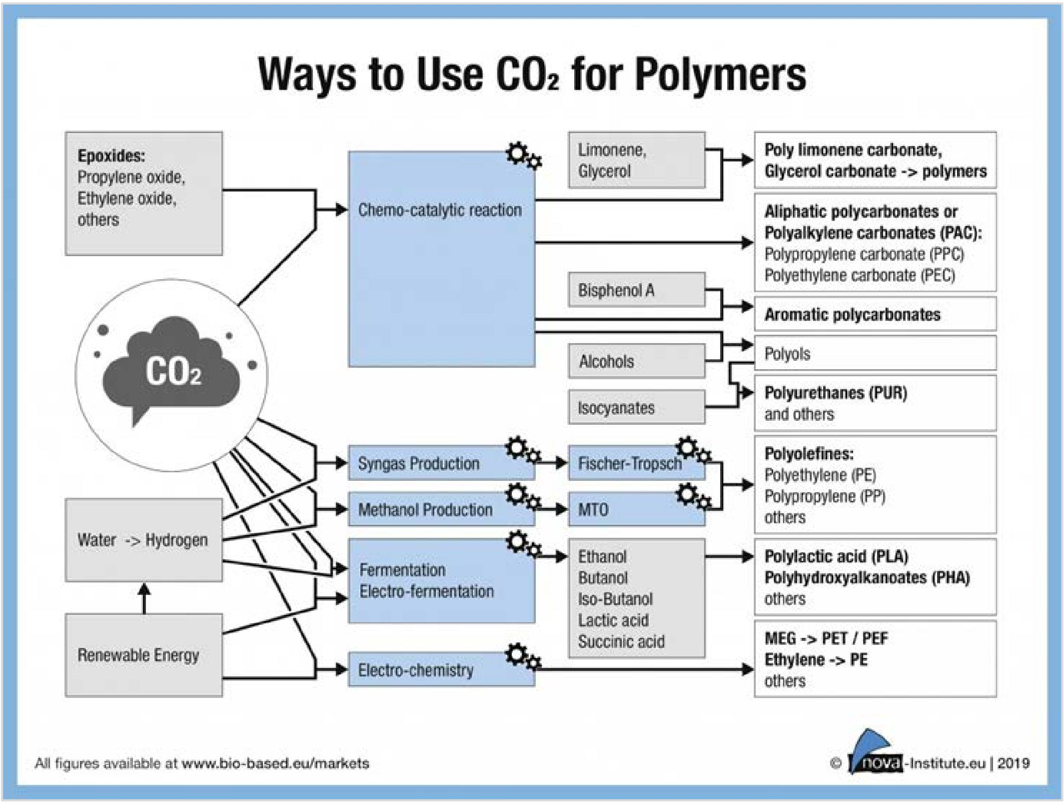
The common part between CCU and CCS is the capture of CO_2, for which several mature technologies are available:

- In pre combustion capture, the hydrocarbon fuel is gasified to carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam to produce carbon dioxide and water[34]. The CO_2 can then easily be captured from the gas stream for example by amine scrubbing, as is the industry standard in ammonia production (EC, 2007).
- Post combustion capture can be retrofitted to virtually every combustion process. The combustion itself remains unchanged, but the CO_2 is captured from the flue gas, usually by amine scrubbing. Capture costs per ton of CO_2 are lower for higher CO_2 concentrations. While the amine capture technology is mature, the process is not economically viable at the current carbon price, mainly because of the high energy demand of the amine regeneration and the large investments required.
- In oxy-fuel combustion, the fuel is burned in pure oxygen rather than air. By eliminating nitrogen from the air flow, the resulting flue gas stream has a higher CO_2 content, which translates into lower capture cost. These gains are however offset by the cost of the pure oxygen required. Oxy-fuel combustion with capture is not yet commercially applied, although several pilot installations exist.
- Direct-air capture is different from the approaches above in that it captures CO_2 from the ambient air rather than from a point source. The most well-known example of this technology is the Climeworks project, which uses calcium hydroxide to capture CO_2. Since air only has a very low CO_2 concentration, huge volumes are required to capture significant amounts of CO_2. The technology works, but is not currently competitive with other capture processes on a cost basis.

Carbon can be reused in an enormous diversity of processes and products. As an example, one study treats 130 different CCU products (EC, 2017). For a schematic overview of potential pathways for polymer production, see Figure 16.

[34] Fuel gasification: $C_xH_y + O_2 \rightarrow CO + H_2$. Water-gas shift: $CO + H_2O \rightarrow CO_2 + H_2$.

Figure 16: Schematic overview of potential pathways to use CO_2 for the production of polymers



Source: (Nova Institute, 2019), used with permission.

It is important to note that the CO_2 reduction of CCU routes is dependent on among others the source of carbon, the energy use of the process, the application of the product and the displaced alternative. In addition, some applications store carbon permanently, e.g. mineralisation, while others store CO_2 only for a short period, e.g. beverage carbonation. Because there are so many parameters influencing the net CO_2 reduction, a full life cycle analysis (LCA) is required to confirm the actual benefits of a certain pathway. A similar statement can be made about the costs of CCU technologies. Each route has a different process and replaces a different product. As such, some routes may be competitive with their fossil counterpart and others not.

This report highlights five prominent pathways, selected on technology readiness:

- **Mineralisation**, also known as carbonation, converts mineral oxides or silicates and CO_2 into mineral carbonates. The most well-known example is weathering of the mineral olivine, which has a net absorption of 0.37 kg CO_2/kg mineral (CE Delft, 2017). The product can be used as aggregate in civil construction. CO_2 is permanently sequestered in the mineralisation process.
- **Methanol** can be produced by direct conversion of CO_2 and hydrogen to methanol. Methanol can be further converted into olefins for polymer production, into gasoline or used directly as fuel. Methanol made from renewable electricity yields an emission reduction 350-750 kg/t captured CO_2, depending on the source of the CO_2 and which end product is displaced by the final product made from the methanol (CE Delft, 2018).
- **Polyurethanes** are made by reaction of isocyanates with a polyol. Polyurethanes are rigid foams used in among others mattresses, car seats and shoes. Saudi Aramco's Converge polyol

is produced by reacting propylene oxide with CO_2. The resulting polyols contain up to 40% of CO_2 by mass (Saudi Aramco, 2020).

- **Reuse of steel off gases** instead of combustion in thermal power plants can displace fossil fuel and feeds. ArcelorMittal and Lanzatech's Steelanol process converts steel off gases into ethanol for gasoline blending with a claimed 77% CO_2 emission reduction compared to fossil fuel (ArcelorMittal, 2015). Tata Steel and Dow Chemical are developing the Steel2chemicals process which will produce synthetic naphtha for Dow's steam cracker from carbon monoxide and green hydrogen.
- **Synfuels via Fischer-Tropsch** are produced from CO_2 and green hydrogen in the Fischer-Tropsch synthesis process. Large amounts of renewable electricity are required to produce the hydrogen (Concawe, 2017). Although the Fischer-Tropsch technology is mature, the potential for synthetic fuels is limited due to the much higher prices compared to fossil fuels (Christensen & Petrenko, 2017).

Currently applied CCU pathways outside industry are the use of CO_2 in greenhouses, in carbonated beverages and inert atmosphere for food packaging.

In regulatory terms it is important that reductions due to CCU are to be accounted once. This implies that the CO_2 captured to produce synfuels can either be counted as emission reductions under the EU ETS, or as emission reductions from the user of the synthetic fuels, but it cannot be counted for both uses. The same goes for the electricity used to make CCU products: this should come from newly added renewable generation capacity rather than from the grid to avoid indirect displacement effects.

For CCS purposes, CO_2 can be sequestered by underground storage in empty oil and gas fields or aquifers[35]. Storage in both empty oil and gas fields and aquifers is technically mature, but currently only profitable if the CO_2 is used for enhanced oil and gas recovery. To illustrate the maturity of the technology: the Norwegian Sleipner gas field has seen annual injections of around 1 Mton CO_2 since 1996 (Equinor, 2019). Storage capacity available in Europe is not foreseen to be an issue until 2050, although this is not equally divided over all regions, leading to potential local constraints in available storage capacity (Budinis, Krevor, Mac Dowell, Brandon, & Hawkes, 2018).

The first major barrier for CCS is the cost, mainly caused by the high cost of the capture itself. The estimated added cost of CCS for three products is displayed in the table below. CCS would lead to roughly a doubling in price for cement, while the effect on the price of ammonia is relatively small.

Table 7: Estimated cost of CCS for three core products

Product	Cost of avoided CO_2 [€/t CO_2]	CAPEX [€/t product/y]	OPEX [€/t product]	Product price [€/t]	Price increase with CCS [%]
Steel	65-77	500	130-154	~650	20-25%
Cement	103-124	300	85-103	100	85-105%
Ammonia	24-25	40	13-14	~250	5-6%

Source: Adapted from (Irlam, 2017), product prices from (World Steel Prices, 2020) (EC, 2017) and (FAO, 2020).

[35] Alternatively, CO_2 can be stored by enhanced weathering of olivine bearing minerals, but this technology is not discussed further as it stores atmospheric CO_2 and as such is not relevant for industry (Strefler, Amann, Bauer, Kriegler, & Hartmann, 2018).

For fertilizer production, the cost of avoided CO_2 by employing CCS is close to the current market price of CO_2, yet no fertilizer plants in Europe utilise CCS (Global CCS Institute, 2019). This indicates the presence of barriers other than economic. The lack of infrastructure is considered as the second major barrier for CCS. Finding a suitable reservoir, validating it and obtaining a storage permit are complex, time-consuming processes. Planning and building a pipeline is time and capital-intensive as well. A suitable reservoir is not available in each region, necessitating long distance transport of CO_2, where it is to be stressed that transport other than through pipelines is not acknowledged under current ETS rules.

The capture cost is not a significant barrier for CCU, as the cost of carbon is only a small percentage of the price of most CCU products (CE Delft, 2017). The cost of energy is usually more significant, especially for CCU routes that require large amounts of (green) hydrogen. The net avoided CO_2 of CCU routes is not immediately apparent and an LCA is required for each product and application to verify the benefits.

A.7. Technologies dealing with process intensification

Process intensification is a design philosophy in chemical engineering that drastically decreases the size and hence cost of chemical equipment by thoroughly redesigning the equipment. This reduction is achieved by intensifying heat and mass transfer, applying new separation principles or combining functions conventionally performed by separate pieces of equipment into one (Stankiewicz & Moulijn, 2000). General energy efficiency approaches focus on incremental improvement using existing processes and installations, where process intensification changes the process itself or radically redesigns core parts of the process. While the potential gains of further optimisation of conventional equipment are diminishing as thermodynamic limits are ever closer approached, process intensification can offer a step change by adopting radically new designs. It is estimated that process intensification can offer an improvement of 20% in energy efficiency within the petrochemical sector around 2040 (Creative Energy, 2007).

A well-known example is Eastman's methyl-acetate process that applies reactive distillation. The chemical reaction itself and the product separation are integrated into a single column, where the conventional process uses five columns (Bielenberg & Bryner, 2018). A more recent example is the development of the HIsarna process for steel production, which reduces energy demand and CO_2 emissions by at least 20% compared to a traditional blast furnace (Tata Steel, 2017).

The concept of process intensification has been around since the 1970's, but industry uptake is still limited to a number of niche applications. Bielenberg and Bryner mention the following factors for this slow adaptation:

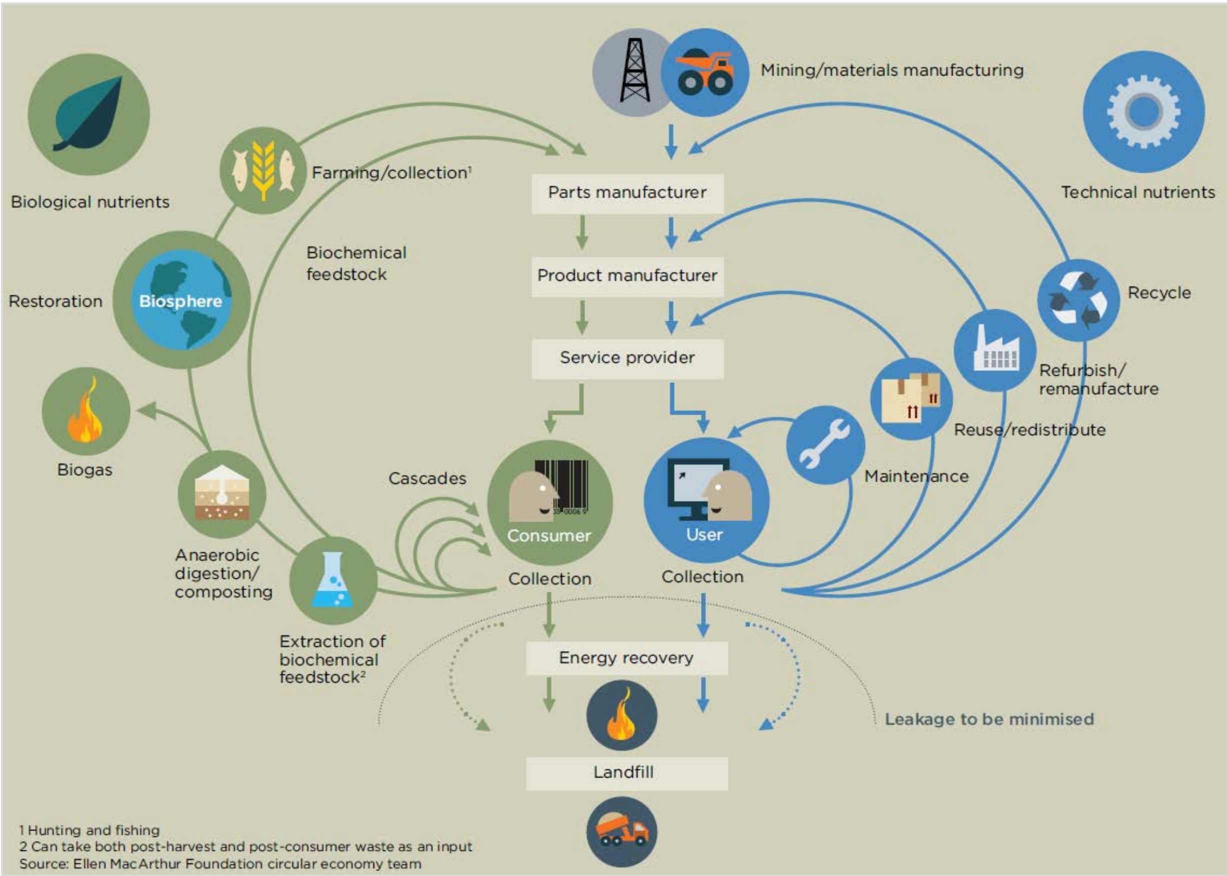
- capital costs and reliability, availability and maintainability risks associated with implementing new processes;
- intensified, modular systems are very complex, no standard equipment and techniques yet exist;
- insufficient software, design tools, and data to develop intensified processes;
- challenges related to the technical, economic, and intellectual property of developing standardised design and manufacturing protocols for a complex new technology space at an early point in its technical and commercial development; and
- limited understanding of design and operation of PI technologies across a broad range of key industry sectors.

It is clear that significant, coordinated R&D efforts are required to unlock the potential of process intensification. Nevertheless, the development and implementation at industrial scale of new and more efficient processes is key to achieve a deep reducing of CO_2 emissions and limit the energy demand of industry. Many existing processes are developed for an environment where energy and especially heat is abundant and cheap. If fossil fuels are no longer to be used, this ceases to be the case. New processes can take full advantage of new technological improvements and do not have to conform to the form factor of the incumbent technology, which opens the door for major improvements in efficiency and production cost.

A.8. Technologies concerning the circular economy

Our current economy is mostly linear: materials are extracted, made into products, used and finally disposed (take-make-use-destroy). The linear economy has a strong focus on production. The circular economy on the other hand puts the product itself and the function it performs at centre stage. When thinking about the function a product has to perform, the sale of a certain new product to the consumer is not the only answer. Instead, the consumer can choose a different product that performs the same function, lease the product, share the product with his neighbour or have his broken product repaired, refurbished or remanufactured. These techniques are illustrated in Figure 17. Since all techniques start with 'Re', they are often termed 3R or 10R, depending on how elaborate the model is. A circular economy is created by using products as efficiently as possible and retaining maximum value when a product eventually breaks or reaches end of life. This means that refurbishment is preferable over recycling, reuse over refurbishment and maintenance over reuse. This preferential order is indicated in the figure by the length of the cycle: shorter cycles retain more value and should thus be applied before the longer cycles.

Figure 17: Graphical representation of the circular economy



Source: (Ellen MacArthur Foundation, 2013).

Multiple techniques can be used in succession: cotton clothes can for example be first reused as second-hand clothing, successively recycled into filling for upholstery and finally processed into stone wool for insulation (Ellen MacArthur Foundation, 2013). This cascading is analogous to the cascading of biomass, also displayed in Figure 17 and previously discussed in Annex A.4.

Transition towards a more circular economy has major benefits:

1. Reduced environmental impact of resource extraction, production processes and waste disposal.
2. Optimised economic efficiency by retaining value.
3. Increased security of supply of materials through substitution of primary inputs by secondary inputs.
4. Lower depletion rate of finite supply of scarce materials.

The impact on the sectors under consideration in this report is partly indirect. Consider for example the steel industry. Car sharing leads to higher utilisation rates of existing vehicles, leading to lower demand for new vehicles, which in turn leads to a lower demand of primary steel. This illustrates that primary material production is affected by adaptation of circular strategies in sectors closer to the end consumer. Circular strategies that can be implemented by the primary production sectors themselves focus mainly on recycling. The most striking technological developments are in the plastics sector, so we will highlight a number of them:

- **Mechanical recycling of plastics** constitutes the separation and reuse of waste plastics without altering the molecules themselves. Recycled granulate can be made into new products with little loss of quality. Mechanical recycling is the method for recycling of plastics if technology is available that yields a sufficiently pure product stream. New sorting methods such as X-Ray detection, Raman spectroscopy and laser sorting are being developed to generate higher purity streams.
- **Chemical recycling of plastics** breaks down the polymer molecules into monomers or even smaller molecules. Multilayer plastics, composites, or highly contaminated streams are not currently eligible for mechanical recycling, but can be chemically recycled. While some technologies recover a pure monomer stream by depolymerisation, such as solvolysis, most chemical recycling routes are currently aimed at the production of liquid fuels: pyrolysis, fluid-catalytic cracking and gasification. The addition of hydrogen in hydropyrolysis, hydroconversion and hydrocracking processes lowers coke formation, lowers acidity and removes impurities, improving overall fuel quality. Few industrial scale installations for chemical recycling exist and significant efforts are being made to improve the selectivity of the technology such that pure streams with the same quality as virgin material can be produced.
- **Information management** is critical for a maximum conservation of value along the product chain. Recycling is made much more effective when for the exact composition of each part and product is known. As an example, an accurate assessment of the contents of a batch of scrap steel can prevent copper contamination, thus allowing the recycled scrap to be used in high-strength applications instead of downgrading it to construction steel. Determining the contents of produced products and conserving this information until the end of the product life is key to improving recycling strategies further.

Although the techniques for a circular economy are well-documented, they are not yet widely implemented. The European Green Deal (EC, 2019) says the following about the challenges of transition towards the circular economy in the European Union: *"From 1970 to 2017, the annual global extraction of materials tripled and it continues to grow, posing a major global risk. About half of total greenhouse gas emissions and more than 90% of biodiversity loss and water stress come from resource extraction and processing of materials, fuels and food. The EU's industry has started the shift but still accounts for 20% of* *the EU's greenhouse gas emissions. It remains too 'linear', and dependent on a throughput of new materials extracted, traded and processed into goods, and finally disposed of as waste or emissions. Only 12% of the materials it uses come from recycling."*

Adaptation of the circular economy could lead to an emission reduction of up to 60% in industry 2050 (EC, 2018) by requiring less virgin material and reduced energy demand of the processes associated with the 10R strategies compared to primary manufacturing. The transition to a more circular economy is at least as much a societal and business model change as it is a technological change. Economy-wide changes are required as opposed to technologies such as electrification or CCS, which only require the adaptation of manufacturing equipment and additional infrastructure. While the shorter cycles in Figure 17 offer increased economic and environmental benefits over the longer cycles, their implementation is generally more challenging from a supply chain and consumer behaviour perspective. As a start for the implementation of a circular economy, increased waste management and recycling practices offer energy and emission reductions without major adaptation of business models. Going further, changes in product design to optimise reuse, maintenance and remanufacture, changes in use patterns and product-as-a-service business models require more transformative changes while at the same time offering enhanced benefits. The transition to full circularity offers again larger benefits, but at the same time even deeper transformation of consumer behaviour and business models is required.

While the adaptation of circular strategies generally represents a reduction in energy demand and emissions, this is not necessarily the case, especially if the process to reuse materials is energy-intensive. The positive impact of circular products should be confirmed by using standardised life cycle assessment (LCA) methodology.

There is a body of literature discussing the barriers to the circular economy. Kirchherr et al. suggest that cultural factors constitute the main barrier to the implementation of a circular economy (Kirchherr et al., 2018). They list lacking consumer interest and awareness, hesitant company culture, low virgin material prices, operating in a linear system and high upfront investment costs as the five most pressing barriers, based on a large survey. Technological barriers are perceived as the least pressing. This analysis suggests that policy should focus not on technological improvements but rather on cultural factors and improvement of the business case of circular products compared to fossil alternatives.

ANNEX B. EXTENSIVE OVERVIEW OF FUNDING MECHANISMS

B.1 European Fund for Strategic Investments (EFSI) and EFSI 2.0

Objective: Closing investment gap after financial crisis

Measures: Funding inter alia infrastructure, education, renewable energy and energy efficiency projects

Budget: EUR 16 billion guarantee by EU budget and EUR 5 billion provided by EIB (EFSI), additional EUR 10 billion guarantee by EU budget and EUR 2.5 billion provided by EIB (EFSI2.0) until 2020.

Duration: 2015-2020 (EFSI & EFSI2.0)

After the financial crisis, the EU intended to boost the European economy through funding programmes. One of the challenges identified was that, across the EU, investment levels were deemed too low – the so called "investment gap". The multi-billion European Fund for Strategic Investments (EFSI) – also called the Juncker plan – and its successor the EFSI 2.0 are direct responses to address the investment gap and support funding for inter alia infrastructure, education, renewable energy and resource efficiency.

The EFSI is an initiative launched by the EIB group (European Investment Bank and European Investment Fund) and the European Commission in 2015. In its initial programming period, a total amount of EUR 16 billion was guaranteed by the EU budget with an additional EUR 5 billion provided by the EIB (Regulation (EU) 2015/1017). The EU budget guarantee with its first loss protection enables the EIB group to provide investments for higher-risk projects than they normally would. The total amount of EUR 21 billion were distributed through two different windows or thematic areas: the infrastructure and innovation window and the Small and Medium Enterprise (SME) window – with the former being deployed by the EIB and the latter by the European Investment Fund (EIF). The EU budget guarantee and the directly provided EIB amount were expected to catalyse EUR 60.8 billion by the EIB group, which in turn were set to induce overall investments of EUR 315 billion in the Union.

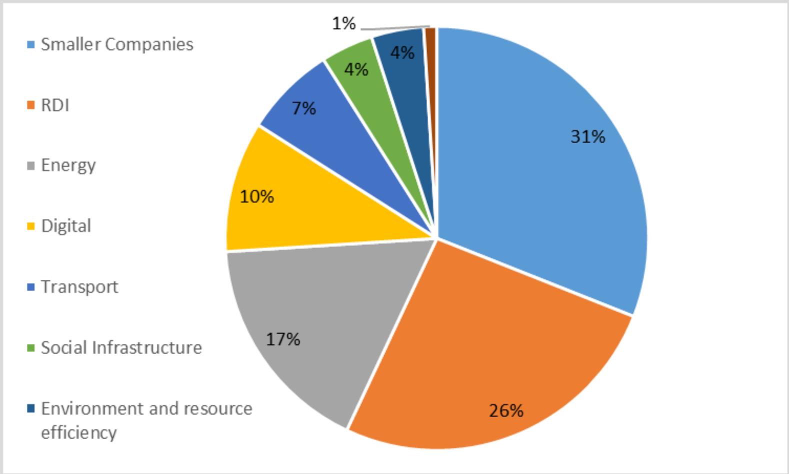
In 2017, the loan guarantee was raised to a total amount of EUR 26 billion and the EIB's contribution to EUR 7.5 billion (Regulation (EU) 2017/2396). The total amount of EUR 33.5 billion was set to generate EUR 100 billion in additional investments by the EIB group. Overall, the aim was to unlock total investments of at least EUR 500 billion by the end of 2020.

Projects that can receive financing by the EFSI need to undergo the standard EIB due diligence process. In particular, EFSI projects need to be economically and technically sound, they need to be eligible in at least one of the sectors defined in Article 9 of the EFSI regulation (Regulation (EU) 2015/1017), they need to contribute to EU objectives, including sustainable growth and employment, and they need to be mature enough to be bankable and priced in a manner commensurate with the risk taken.

According to Article 9 of the EFSI regulation, a variety of sectors and objectives are eligible for funding. For instance, research projects, which are in line with the Horizon 2020 or demonstration projects as well as deployment of related infrastructures, technologies and processes, can apply. Further, the article lists academia projects including collaborations with industry. Explicitly mentioned are the EU 2020, 2030 and 2050 climate and energy frameworks. Hence, for example, projects that promote renewable energy use are eligible to apply for funding. Although not explicitly mentioned in the related documents, the fund could also support CCS and CCU projects. The programme already funds measures in energy-intensive industries to improve their energy efficiency and reduce carbon emissions.

Figure 18 gives an overview of the share of investments per sector. Next to smaller companies (31%), the majority of the funding went to Research, Development and Innovation (RDI) projects (26%). Energy-related projects received 17% of the overall EFSI funding, whereas the sector Environment and Resource efficiency only accounted for 4%. While some of the projects in the energy as well as the environment and resource efficiency sector are financed for R&D, the majority relate to CAPEX – for instance investments into new PV installations or upgrading existing installations to increase their energy efficiency.

Figure 18: Share of Investments across Sectors as of 05/02/2020



Source: European Commission (2020). Investment Plan results. https://ec.europa.eu/commission/strategy/priorities-2019-2024/jobs-growth-and-investment/investment-plan-europe-juncker-plan/investment-plan-results_en

Examples of EFSI-supported investments in energy-intensive industries

The Spanish steel company Sidenor invested into measures to enable manufacturing of higher quality special steels products and the development of new products to enter new industry segments, as well as improving energy efficiency. With total project costs of EUR 128 million, these investments were supported with approximately EUR 50 million by the EFSI for research, development and innovation as well as CAPEX funding for new equipment and facilities as well as digitalisation.
Another steel company situated in Germany – the Hüttenwerke Krupp Mannesmann – received EUR 60 million EFSI funding for the modernisation of an existing integrated steel plant to improve its environmental performance as well as to reduce energy consumption and CO_2 emissions through the installation of new equipment. The project's overall costs are EUR 120 million. It is estimated that the project will result in yearly emission savings of 469 kt of CO_2.

The German company Salzgitter Steel received EFSI funding of EUR 150 million for an overall EUR 331 million project, which supports RDI in order to promote the company's technological know-how in its field of iron and steel making as well as beverage filling and packaging equipment. Hereby, the project aims to increase energy efficiency and therefore reduce CO_2 emissions. The project also benefits from national financial support as well as EU grants under the Horizon 2020 research programme.

All projects funded by the EFSI can be found here: https://www.eib.org/en/efsi/efsi-projects/index.htm?q=&sortColumn=boardDate&sortDir=desc&pageNumber=0&itemPerPage=25&pageable=true&language=EN&defaultLanguage=EN&statuses=signed&orstatuses=true&abstractProject=false&orabstractProject=true&yearFrom=2015&yearTo=2020&orCountries=true&orSectors=true

B.2 Programme for Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME)

Objective: Enhancing the competitiveness of European SMEs

Measures: Facilitating SMEs financing, access to markets, entrepreneurship and creating better framework conditions for competitiveness

Budget: EUR 2.3 billion

Duration: 2014-2020

In order to improve the competitiveness of SMEs, the European Parliament and the Council have established the EU programme for the Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME) in 2013. They committed to invest up to EUR 2.3 billion in European SMEs from 2014 to 2020 (Regulation (EU) 1287/2012). In particular, the programme aims to make SMEs more competitive by facilitating their financing, supporting their access to new markets, encouraging entrepreneurship and creating better framework conditions.

Eligible for the COSMEs funding are SMEs in their start-up, growth and transfer phase. COSME funding is aligned with sustainability goals, as it is designed to promote the adaptation of low-emission, climate-resilient, resource- and energy-efficient business practices as defined in article 4 of the COSME regulation (Regulation (EU) 1287/2012). COSME includes two different financing facilities: the equity facility of growth provides companies with venture capital to support growth, research and innovation projects (article 18). The Loan Guarantee Facility can grant guarantees for debt financing to eligible SMEs (article 19). Both facilities are managed by the European Investment Fund or by other entities entrusted with the implementation on behalf of the European Commission.

As COSME focuses on low-emission and energy-efficient projects, the fund is appropriate for supporting companies' further market deployment of low-carbon technologies, which may include CCS and CCU. With its clear focus on SMEs the fund complements the other programmes and funding instruments. However, COSME's overall budget is relatively small.

EII Case study

In 2015, COSME has assigned a contribution of EUR 1.4 million to a consortium of micro and small enterprises in central Italy in the context of the "Small and Medium Enterprises to European Union (SME2EU)" project. The participating companies received funding to uphold their excellence and innovation against the international competition. They were operating in different industries, inter alia the aerospace, automotive, wood and furniture, but, also within the chemical market. Hence, the COSME's funding has partially contributed to investments in the EII, by supporting the Italian chemical industry.

B.3 European Structural and Investment Funds (ESIF)

Objective: Promoting economic, social and territorial cohesion

Measures: Funding investments in research and innovation, digital technologies, sustainable management of natural resources, small businesses and supporting the low-carbon economy

Budget: EUR 461 billion

Duration: 2014-2020

The ESIF was designed to support the implementation of the Europe 2020 strategy, in which the European Union has committed to foster employment and a socially inclusive society in all member states. To this end, ESIF is intended to support the economic, social and territorial cohesion of the European Union. ESIF includes five different funds: European Regional Development Fund (ERDF), European Social Fund, Cohesion Fund, European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund. The European Commission and the member states jointly manage these funds. Combined, they represent over half of overall EU funding.

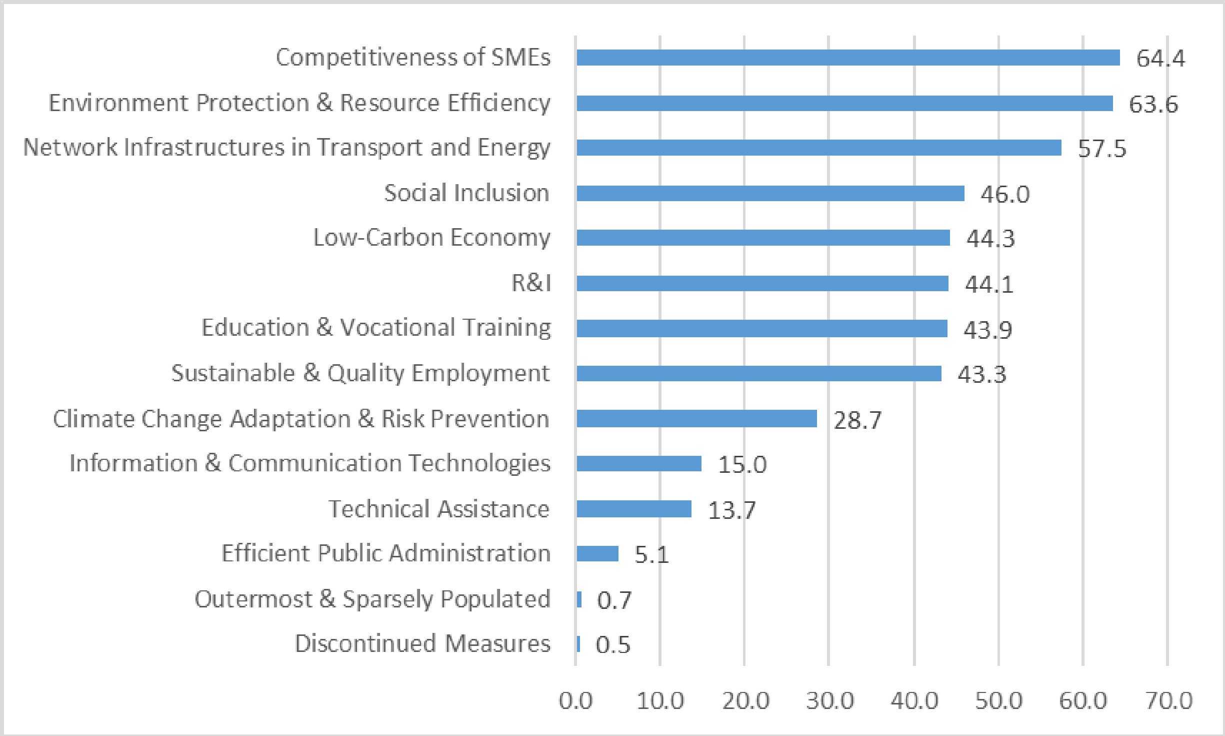
The different funds all have their respective focus areas: Thus, the Cohesion Fund supports exclusively transport and environmental projects in less-developed member countries; the European social fund contributes to the adaptability of workers and enterprises and supports the access to employment and participation in the labor market. The European regional development fund focuses its investments on the following priority areas: innovation and research, the digital agenda, supporting SMEs as well as low-carbon economy. In particular low-carbon economy projects are addressed. 20% of the projects funded under the ERDF in more developed regions need to specifically relate to a low-carbon economy, whereas in transition regions and less developed regions the corresponding share needs to be 15% and 12%, respectively. Combined, these funds account for a total funding amount of EUR 461 billion between 2014 and 2020.

As defined in Article 4 of the ESIF Regulation (Regulation (EU) No 1303/2013), funding will only be provided to investments that respect the principle of a sound financial management. Moreover, it is preconditioned that the ESIF provides only support to investments that align with the Union's strategy for a smart, sustainable and inclusive growth and cohesion. This includes the consideration of environmental protection requirements, resource efficiency, climate change, mitigation and adaptation and biodiversity, as mentioned in article 8 (Regulation (EU) No 1303/2013).

This makes the programme suitable for financing low-carbon technologies. With its distinct provision to support inter alia climate-related projects and with its focus on less developed European regions, the ESIF can not only enhance technology's market deployment but specifically foster economic development in marginalised regions with the support of local companies.

Figure 19 depicts the overall ESIF funding divided by themes. Direct investments in sustainable development, including environment protection and resource efficiency (EUR 63.3 billion), low-carbon economy (EUR 44.3 billion), climate change adaptation and risk prevention (EUR 28.7 billion), together account to almost one third (29%) of the total ESIF funding. This share could be higher still since investments in sustainable development are partially included in other themes, such as R&I or network infrastructure in transport and energy. Nevertheless, most investments of the ESIF were allocated to economically-related topics like, for instance, competitiveness of SMEs (EUR 64.4 billion).

Figure 19: Total ESIF Budget by Theme (in billion EUR)



Source: European Commission. European Structural and Investment Funds. Data. https://cohesiondata.ec.europa.eu/dataset/ESIF-Regional-Policy-budget-by-country-2014-2020/fift-a67j

EII Case Study

The steel industry has benefited from the Integrated Strategic Energy Plan of the ESIF in 2015. EUR 44 billion of the plan were dedicated to regional research and innovation strategies. Some regions in the Czech Republic, Slovakia, Spain, Finland and Sweden have included support in modernising the regional steel industry. It was an opportunity for the participants to exchange their experiences and technologies, in order to improve their energy efficiency or adapt new technologies within their business field.[36]

B.4 Horizon 2020

Objective: Supporting European research and innovation to ensure Europe produces world-class science, remove barriers to innovation and strengthen private and public research cooperation

Measures: Funding a research and innovation programme with a call for proposal mechanism

Budget: EUR 80 billion

Duration: 2014-2020

[36] European Commission (2016). Steel: Preserving sustainable jobs and growth in Europe. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_16_805

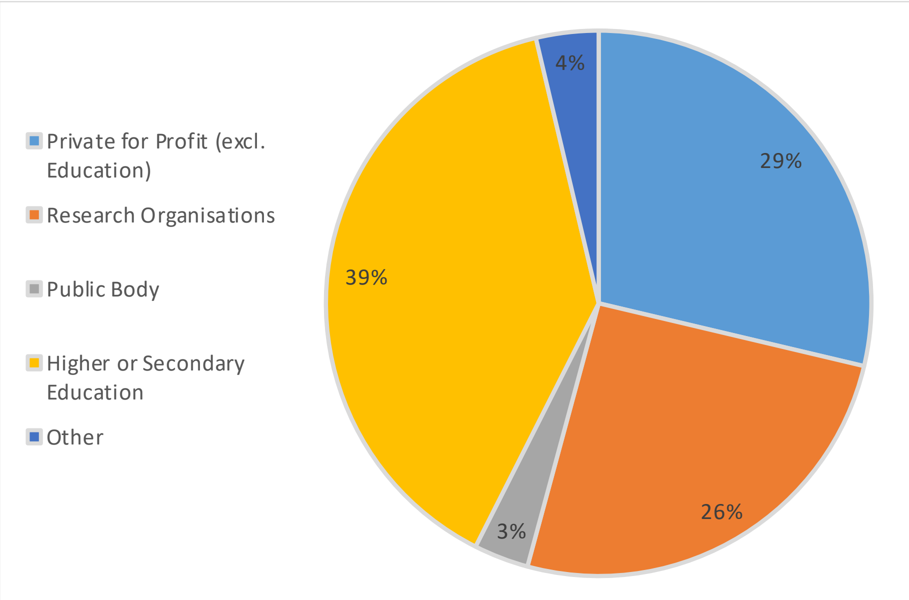
The Horizon 2020 programme provides nearly EUR 80 billion for research and innovation in the period of 2014-2020. Its goal is to secure Europe's global competitiveness, invest in innovative future jobs and growth and to address people's concerns about their livelihood, safety and environment.

The European Commission sets a work programme announcing the specific areas that will be funded under Horizon 2020. Scientific institutions and innovators can apply for funding under open calls. As stated in Article 2 of the Horizon 2020 regulation, the fund covers the whole spectrum of research, technological development, demonstration and innovation, education, the dissemination and optimisation of results (Regulation (EU) No 1291/2013). Particularly, the programme supports the development of new processes and technologies that reinforce sustainability.

The Horizon 2020 programme is best suitable for technology development in early stages. The programme funds basic scientific research, not necessarily geared towards delivering economically competitive technologies. At the same time, the large budget enables the support of costly research projects, including for industrial innovation projects such as the development of low-CO_2 iron and steelmaking, for instance.[37]

A cross section of the share of Horizon 2020's funding by recipient is illustrated in Figure 20. Most of the funding from Horizon 2020 was granted to educational institutions (39%), followed by private for profit (29%) and research organisations (26%).

Figure 20: Share of Horizon 2020 funds across types of organisations



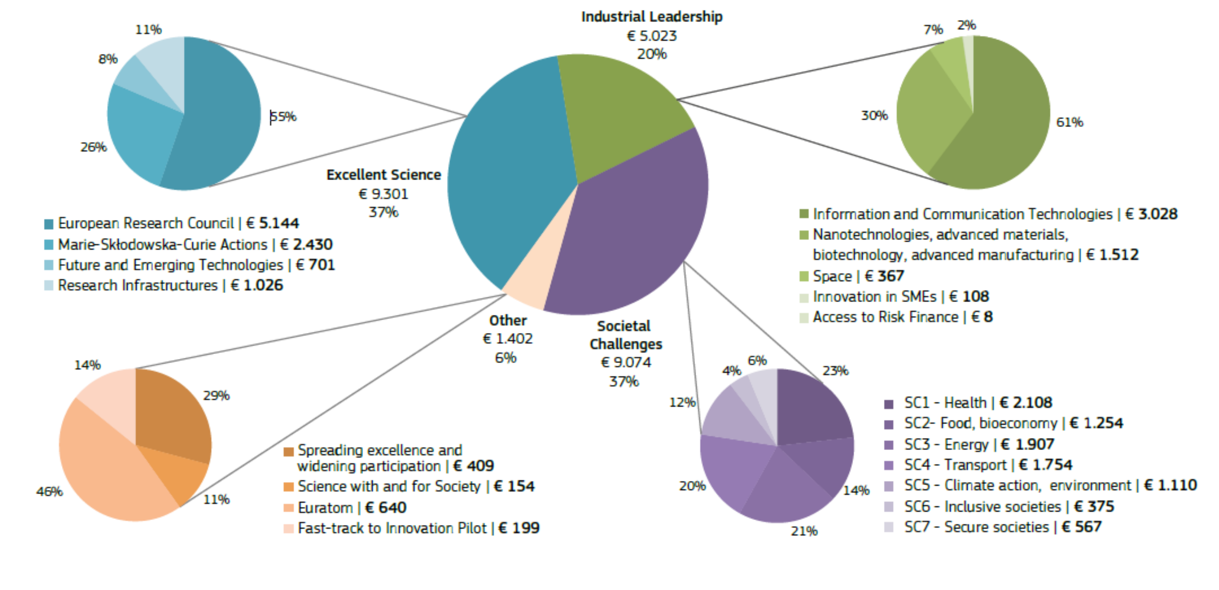
Source: European Commission, H2020 Country Profile, https://webgate.ec.europa.eu/dashboard/sense/app/a976d168-2023-41d8-acec-e77640154726/sheet/0c8af38b-b73c-4da2-ba41-73ea34ab7ac4/state/0

Figure 21 gives an exemplary overview of EU contribution to signed grants per programme part between 2014 and 2016. The biggest contributions are given within the programmes 'Excellent Science' and 'Societal Challenges' with both receiving 37% of all contributions (between EUR 9 billion and EUR 9.3 billion). The 'Industrial Leadership' programme receives 20% or around EUR 5 billion. The

[37] European Commission, Cordis, Project Information LoCO2Fe, available at: https://cordis.europa.eu/project/id/654013

first case study below (in the box), for instance, is funded within the 'Industrial Leadership' programme, whereas the latter two are funded within the 'Societal Challenges' programme.

Figure 21: EU Contribution to signed grants per programme part (EUR million) in 2014-2016



Source: Corda, calls in 2014, 2015 and 2016, Signed Grants cut-off date by 1/09/2017 (including grants to named beneficiaries)

EII Case Study

Despite these opposing barriers for the EII, funding has been granted in their interest. For instance, a contribution of nearly EUR 5 million were allocated from the Horizon 2020's budget for research and innovation actions in the steel industry. Fifteen participants developed a laser technology for electrical steel structuring, insulating and assembling to support the European industrial base while reaching the energy transition agenda. [38]

Under the Horizon 2020 funding framework a project was financed implementing the use of CCS for power production. The resulting new solvents and membranes can also contribute to a useful capture technology in the cement, steel and aluminium industries. Overall, the fund granted EUR 4.3 million for the project, which in total costed a little more than EUR 6 million. [39]

Another project funded by the Horizon 2020 progamme developes an integrated process, which produces methanol from CO_2, recovered from the blast furnace gas of an industrial steelmaking plant, and H2 recovered either from the blast furnace gas or produced by electrolysis. The project costs of almost EUR 11.5 million were entirely funded by the programme. [40]

[38] European Commission. Cordis EU research results. Available at: https://cordis.europa.eu/project/id/766437

[39] European Commission. Horizon 2020. Clean and efficient CO2 capture. Available at: https://ec.europa.eu/programmes/horizon2020/en/news/clean-and-efficient-co2-capture

[40] European Commission. INEA. FReSMe. Available at: https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/carbon-capture-and-storage/fresme

B.5 Just Transition Fund

Objective: Reduce emerging regional disparities caused by the transition towards a climate-neutral economy

Measures: Investments in SMEs, R&I, deployment of technology and infrastructure, digitalisation, circular economy and job-search assistance and consultation

Budget: EUR 7.5 billion

Duration: 2021-2027

The transformation to a climate-neutral economy could threaten to leave some regions behind, leading to growing regional disparities and, as a result, resentment. Therefore, the JTF aims to reduce regional disparities and to address structural change in Europe's regions. In Article 2 of the Just Transition Proposal, it is defined that the single specific objective of the programme is to enable regions and people to address the social, economic and environmental impacts of the transition towards a climate-neutral economy (Proposal 2020/0006 (COD)). This will be achieved by funding investments in SMEs, R&I, deployment of technology and infrastructure – focusing on clean energy, greenhouse gas reductions, energy efficiency and renewable energy -, digitalisation, circular economy and job-search assistance and consultation (Article 4: Proposal 2020/0006 (COD)). For these ends, the JTF has an absolute budget of EUR 7.5 billion available for the 2021-2027 period.

As the Commission's proposal states, the fund's scope and objective is not only to address the impact of transition towards climate neutrality and the situation of solid fossil fuel extraction activities, but also to include the transformation of energy-intensive industrial processes. The fund is explicitly intended to support regions that rely to a great extent on "greenhouse gas-intensive industries". Although the proposal does not specifically mention energy-intensive industries, the fund's broad objectives leave the possibility that EIIs could also benefit from support. Combining the broad objective with the potential support of investments in the deployment of new technologies, financing EII specific technologies can be within the scope of the funding programme.

B.6 Innovation Fund

Objective: Create financial incentives for next generation of technologies projects, boost growth and competitiveness, supporting low-carbon technologies in all Member States

Measures: Funding highly innovative technologies and big flagship projects

Budget: EUR 8-15 billion depending on carbon price

Duration: 2020-2030

The Innovation Fund (IF) is established by Article 10a (8) of the EU ETS Directive to support innovation in low-carbon technologies and processes in sectors participating in the EU ETS. Relevant projects eligible for funding include innovative renewable energy technologies (including energy storage), the construction and operation of projects for the environmentally safe capture and geological storage of CO_2 (CCS), carbon capture and utilisation of CO_2 (CCU), as well as alternatives to carbon-intensive products. It is set to offer financial support and attract additional public and private financial resources.

Further, it will fund sufficiently mature projects in terms of planning, business model, financial and legal structure as well as projects with the biggest innovation potential.

Revenues for the fund originate from the EU ETS – the auctioning revenue from at least 450 million allowances auctioned in the period 2020 to 2030. Further, the fund will receive financial resources from unspent funds of the NER300 programme (which in some ways can be seen as a predecessor to the Innovation Fund). Depending on the carbon price in the EU ETS, the fund may amount up to EUR 8-15 billion.

The Innovation Fund is intended to share some of the risk of transformative investment projects by granting up to 60% of the additional capital and operational costs of the project. Before the project is running, the fund can finance up to 40% of these costs when pre-defined milestones are reached. Compared to the NER300, the Innovation Fund provides more flexible support by following the cash flow needs of the project through pre-defined milestones. Grants from the Innovation Fund can be combined with other funding programmes such as the Horizon Europe (the successor of the Horizon 2020 programme), the Modernisation or Cohesion Fund. The Innovation Fund's financial focus is planned to lie on project's pilot to demonstration phase but also, lastly, the scale-up phase. [41]

Overall, the fund is set to finance highly innovative and big flagship projects. But also smaller projects with total capital costs under EUR 7.5 million can be financed by the fund. The fund is open for applications from all Member States. The funding explicitly addresses the following sectors and technologies: energy-intensive industries, renewable energy, energy storage as well as CCS and CCU.

[41] European Commission. DG CLIMA. Innovation Fund. Available at: https://ec.europa.eu/clima/policies/innovation-fund_en

Energy-intensive industries need to reach climate neutrality by 2050. This study describes the technologies available for the decarbonisation of the iron and steel, chemicals, refining and cement industries as well as the existing financial instruments. Technology and policy roadmaps are presented to help shape the Green Deal and enhance the transition to a climate neutral European industry.
This study was provided by the Policy Department for Economic, Scientific and Quality of Life Policies at the request of the committee on Industry, Research and Energy (ITRE).

PE 652.717
IP/A/ITRE/2020-10

Print ISBN 978-92-846-6794-9 | doi:10.2861/923519 | QA- 02-20-421 -EN-C
PDF ISBN 978-92-846-6795-6 | doi:10.2861/427814 | QA- 02-20-421 -EN-N