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THEMA CONSULTING GROUP

The role of Carbon Capture and Storage in a Carbon Neutral Europe

Assessment of the Norwegian Full-Scale Carbon Capture and Storage Project's Benefits

This report was prepared by Carbon Limits AS and THEMA Consulting Group.

Project title:
The role of Carbon Capture and Storage in a Carbon Neutral Europe

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Report title:	Assessment of the Norwegian Full-Scale CCS project's benefits
Finalized:	3 July 2020

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Carbon Limits works with public authorities, private companies, finance institutions and non-governmental organizations to reduce emissions of greenhouse gases from a range of sectors. Our team supports clients in the identification, development and financing of projects that mitigate climate change and generate economic value, in addition to providing advice in the design and implementation of climate and energy policies and regulations.

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List of abbreviations

ATR	Auto-Thermal Reforming
Bcm	Billion cubic meters
BECCS	Bioenergy with Carbon Capture and Storage
BNEF	Bloomberg New Energy Finance
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CEF	Connecting Europe Facility
CEWEP	Confederation of European Waste-to-Energy Plants
COD	Ordinary Legislative Procedure (ex- CoDecision Procedure)
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DACCS	Direct Air Capture CCS
DKK	Danish Crown
DNSH	Do No Significant Harm
EEA	European Economic Area
EED	Energy Efficiency Directive
EFTA	European Free Trade Association
EGD	European Green Deal
EJ	Exajoule (10^{18} joules)
E-PRTR	European Pollutant Release and Transfer Register
ERA	European Research Area
ESR	Effort Sharing Regulation
ETS	Emissions Trading Scheme
EU	European Union
EUA	EU (Emissions) Allowances
EUR	Euro
GBP	British pound
GCCSI	Global CCS Institute
GDP	Gross Domestic Product

GHG	Greenhouse gases
Gt	Gigatonnes (10^9 tonnes)
GW	Gigawatt
H_2	Hydrogen
IIA	Inception Impact Assessment
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
JTM	Just Transition Mechanism
kt	Kilotonnes
kt/y	Kilotonnes per year
LCOE	Levelized Cost of Energy
LPG	Liquified petroleum gas
LTS	Long-Term Strategy
LULUCF	Land-Use, Land-Use Change and Forestry
Mt	Million tonnes
Mt/y	Million tonnes per year
MW	Megawatt
MWh	Megawatt-hour
NCD	Norwegian Carbon Capture and storage Demonstration project
NECP	National Energy and Climate Plan
PCI	Projects of Common Interest
PEM	Proton-exchange membrane
RED	Renewable Energy Directive
RES	Renewable Energy Sources
SEK	Swedish crown
SMR	Steam Methane Reforming
t	Tonnes
TEN-E	Trans-European Energy Networks
TWh	Terawatt-hour
UK	United Kingdom
USD	United State Dollar
WBSCD	World Business Counselling for Sustainable Development
WTO	World Trade Organisation

Executive summary

The Norwegian full-scale carbon capture and storage (CCS) project is planned to demonstrate a novel CCS value chain with carbon capture at one or two Norwegian industrial facilities, transport of CO_2 by ship and offshore pipeline, and long-term CO_2 storage in a saline aquifer offshore. The main societal goal of the project is to demonstrate carbon capture and storage, thereby providing the necessary development of the technology such that the long-term climate goals of Norway and the EU can be achieved at the lowest possible cost. While the costs and the direct emission reduction impacts of the project are well defined, benefits beyond the project boundaries and over time are difficult to quantify. The project might spur deployment of other projects and hence help drive down CCS costs and can also incite policy and regulatory changes with the aim to promote CCS as an alternative in climate change mitigation. The emerging rise in the ambition level of European climate policy (encompassing countries of the European Union and the European Economic Area) makes it likely that the benefit of the Norwegian full-scale CCS project will increase, both directly for the project itself, but also in terms of other benefits which indirectly can be ascribed to the project. This report explores the possible nature and scale of such benefits.

Specific policies and measures consistent with announced new and stricter emission reduction targets are yet to be defined. Consequently, it is difficult to predict the impacts on CCS deployment and additional benefits to be created by the Norwegian full-scale CCS project. The new and more ambitious climate policy is at an early formative stage and the emphasis of this analysis has been to explore how it might further unfold both at the EU level, at the national level and with companies and planned projects. The purpose of the report is to assess possible impacts for CCS deployment and demonstration effects from the Norwegian full-scale CCS project, but also how the Norwegian project might influence policy making in this formative phase.

The analysis has been conducted by focusing on four main themes and with emphasis on geography and sectors of importance for the Norwegian full-scale CCS project:

1) **The potential role of CCS in six key sectors and in hydrogen production** (chapter 2) with emphasis on exploring the competitive position of CCS versus other alternatives. The technical ranges of CCS deployment in a carbon neutral Europe are estimated.
2) **Targets and policies initiated at the EU level** (chapter 3) focusing primarily on the European Green Deal (EGD) targets, policies and instruments being of particular importance for CCS or alternative abatement measures.
3) **Policies and plans at the national level of nine countries** with emphasis on relevance for CCS and hydrogen production or use (chapter 4).
4) **A review of CCS projects** currently planned and being considered relevant for this analysis (chapter 5).

The analysis and conclusions from these parts form the basis for the assessment of benefits from the Norwegian full-scale CCS project as a result of increased ambitions in European climate policies. As with other analysis of societal cost benefit assessments made for the Norwegian full-scale CCS project, four broad categories of benefits are considered: demonstration value, value of stored emissions, productivity gains, and impacts on Norwegian industrial development.

The key conclusions from the analysis are summarized below.

The potential role of CCS in six key sectors and hydrogen production

CCS is the principal solution for achieving deep cuts in emissions from cement and waste-to-energy. Other sectors have abatement alternatives which makes the scope for CCS more uncertain and sensitive to the direction of technology improvements and costs, as well as EU and national policies.

If each sector were to aspire for carbon neutrality, the role of CCS would be determined by the level of CO_2 emissions and abatement costs of CCS relative to other options. Two sectors have limited opportunities for emission reduction other than through CCS: cement and waste-to-energy. About two thirds of emissions in cement production are process emissions from heating of limestone where carbon capture is the principal abatement option. Use of waste or biomass as an alternative to fossil fuels can allow for some emission reductions. Emissions from incineration of wastes are unavoidable and CCS is the only applicable abatement technology once the waste streams have been generated. Compared to certain other industries, CCS is relatively easy to implement in both sectors. Furthermore, both cement production and waste-to-energy can provide significant shares of biogenic CO_2, allowing for negative emissions when CCS is applied.

We have estimated that applying carbon neutrality for cement production and waste-to-energy generation would require capture and storage in the range of 90–170 million tonnes (Mt) of CO_2 per year. The high estimate is based on an assumptions of stable cement production and current volumes of waste incinerated in waste-to-energy facilities. While the incinerated waste volumes are expected to increase, it seems reasonable to assume a stable volume of fossil-based waste for incineration given targets to increase recycling. The low estimate is based on only process emissions from cement production and reduced incineration of fossil waste.

For other manufacturing industries the ranges are much larger, with a minimum level much below cement and waste-to-energy, but also with a high potential scope depending on the competitive position and political preference for CCS versus other alternatives, see Table 1.

Table 1 - CO_2 emissions, range of potential for capture and abatement costs for key sectors

Sector	Emissions $MtCO_2$ (2017)	Capture by 2050 ($MtCO_2$) Carbon neutral Europe (*)	Abatement costs – current estimates (EUR/tCO_2) (**)
Manufacturing industries			
Iron and Steel	115	11-71 (***)	70-95
Chemical/petrochemical	102	30-39 (***)	39-113
Refineries	130	10-30 (***)	40-359
Cement	122	57-105	60-120
Energy generation			
Waste-to-energy	68	36-60	150-200
Power	1007	0-218	70-105

(*) The low and high estimates reflect the use of CCS versus alternative abatement option. Further, data from different sources with different assumptions have been used, also creating variations in estimates.
(**) All estimates include capture, transport and storage. Estimates vary because of differences in methodologies and underlying data and because different emission sources within each sector have different abatement costs.
(***) Not all emissions are technically capturable

In the iron and steel sector, where there are multiple stages in production, about 50% of total emissions could be reduced by applying CCS on the blast furnace stage. However, to achieve deep emission reductions, the steelmaking process would have to be completely changed, either in a direct smelting process, where CCS could be applied, or in a direct reduction process where hydrogen is used as a reduction agent. Currently it is unclear which of these routes would have the lower abatement costs, as the costs are highly dependent on the prices of hydrogen and electricity. If hydrogen is produced with electricity, high electricity prices will favour smelt reduction using CCS, while low electricity prices favour hydrogen direct reduction.

Chemical and petrochemical production covers a wide range of processes and emission sources with different opportunities for CCS. Ammonia production requires hydrogen typically from natural gas, which can be captured relatively easily (blue hydrogen). Hydrogen can also be produced through water electrolysis (green hydrogen) but the production of green hydrogen currently has a significantly higher abatement cost than blue hydrogen. For petrochemicals and especially plastics production, a number of mitigation options exist. The CCS option appears to have lower costs than other alternatives for deep emission reductions, such as chemical recycling and bio-based feedstocks.

Refineries have a diverse set of CO_2 emission sources of which for some, carbon capture is not feasible. The most relevant source for CCS is hydrogen production used in the refining process, where the CO_2 purity is high. As with hydrogen in ammonia production, the alternative is green hydrogen produced with electrolysis.

Power sector emissions have traditionally been considered the most important facilities for CCS, but this option has lost much of its attraction due to the steep decline in the cost of renewable energy production. The scope for carbon capture in power generation may however change towards 2050 if and when carbon neutrality is not possible to achieve in certain sectors and countries. Then there might be a call for solutions which can offer large-scale negative emissions. Bioenergy with CCS (BECCS) in the power sector is one such option. A number of analyses focusing on future European carbon neutrality include scenarios with a large role for BECCS. This is reflected in the range for carbon capture scope presented in Table 1 above.

Hydrogen is of direct relevance for the scope of CCS in two ways: i) if produced from renewable power ("green hydrogen") it is an alternative to CCS in certain industry processes, or ii) if produced from natural gas ("blue hydrogen") CCS is a solution to achieve deep cuts in emissions from hydrogen production. Considering only the cost of production, blue hydrogen is found to be the cheapest option for large-scale production today. However, the relative competitiveness of blue and green hydrogen in the longer term depends heavily on scale, cost of electricity and gas, and whether consumption is centralised or distributed.

The competitive position of green versus blue hydrogen and the scale of hydrogen production over time will to a significant extent be determined by political framework conditions to be determined at the EU and national level (see discussion below).

Targets and policies initiated at the EU level

While being ambitious in terms of emission reduction targets, the implications of the European Green Deal for CCS will remain highly uncertain until priorities and new policies are decided. Tightening of the ETS market will stimulate CCS, particularly if it is accompanied with measures to address "carbon leakage". Current financial support schemes appear insufficient for substantial CCS deployment unless complemented by policy measures specifically targeted at CCS.

The European Green Deal (EGD) and its supporting legal requirements and policy instruments are likely to call for increased deployment of CCS. It is clear that net-zero GHG emissions in 2050 implies that the cost of emissions will make CCS more financially attractive in certain applications, but its role relative to other mitigation options will depend on framework conditions created by policies and regulations at the EU and national levels that are yet to be decided. Work is ongoing to clarify impacts of the EGD targets and to spell out strategies for priority areas. An industrial strategy has been published and a hydrogen strategy is expected shortly (July 2020). These strategies and other measures such as the Carbon Border Adjustment Mechanism will impact CCS, but much is still unclear and uncertain.

Most analyses published on the role of CCS in a carbon neutral or strongly decarbonised Europe predate EGD, and scenarios diverge greatly. No new scenarios illustrating pathways to achieve a net-zero target for 2050 have yet been presented by the EU as part of the EGD. Net-zero scenarios developed by the EU in 2018 indicate CCS application in manufacturing industries in the range of 70–80 $MtCO_2$/y in 2050. One of the scenarios shows large additional amounts of CO_2 capture from the power sector by 2050 (around 220 $MtCO_2$/y), mainly driven by the need for CCS on biogenic CO_2 emissions due to “failure” of certain sectors and countries to achieve carbon neutrality. These scenarios should be interpreted with caution, as they mainly serve to explore the impact of various decarbonisation options and do not represent concrete policy measures nor targets for different abatement alternatives.

The European Commission only expected to propose the 2030 reduction target in 2021. The target will be set between 50% and 55% below the 1990 level. Both will require a strengthening of policies and regulations to be imposed at the EU level, and proposals to this effect are expected to accompany the proposed target increase. The proposals must thereafter be discussed and approved by the Parliament and Member States.

Little is currently known about the policy mix to reach the 2030 target, including the future role of the emission trading system (ETS) versus other instruments. Assuming that emission reductions in the ETS increase proportionally to its current share, some analyses indicate an increase in the price of EU allowances (EUAs) in 2030 from 29 EUR/EUA with the current 40% reduction target to 52 EUR/EUA with 50% reduction and 76 EUR/EUA with 55% reduction. Simultaneously with the discussions on the target increase, discussions on several other factors that can influence the EUA price development are taking place. This includes the expansion of the ETS to new sectors and support for decarbonisation efforts in ETS sectors.

The estimates of EUA price increases in response to stricter emission targets indicate a potentially significant impact on the financial viability of CCS projects (and other abatement options) already in 2030. As a result, tightening of the ETS market can reduce the need, per CCS project, for other support schemes and as such open up for support for more projects.

The extent to which the EU can rely on high EUA prices to drive decarbonisation of industrial sectors may also rely on simultaneous efforts to establish effective measures to prevent European industry from losing market shares due to costly climate policies, a phenomenon known as ‘carbon leakage’. The Commission’s proposal for a Carbon Border Adjustment Mechanism (CBAM), which is expected in 2021, is a central initiative to address this issue. The CBAM could ensure that the costs of climate policies can be passed on from the industry to final consumers in Europe. However, significant design challenges must be overcome to ensure that the mechanism effectively prevents carbon leakage, and it is therefore still uncertain when and in which form a CBAM will be proposed.

The two most important financial support schemes for CCS at the EU level are the Innovation Fund and the Connecting Europe Facility (CEF). Each of these schemes can provide support for projects in different areas, including CCS. The Innovation Fund, funded from auctioning of EUAs, is currently estimated to accumulate EUR 10 billion for the period 2020–2030 (assuming an EUA price at the current level, 22 EUR). With an increase in the EUA price in response to a tighter 2030 target, the resources available from the Innovation Fund could increase significantly. The focus areas for funding from the Innovation Fund are CCS and CCU, innovative renewable energy, low-carbon technologies in energy-intensive industry, and energy storage. Support to cross-border energy infrastructure projects through CEF are expected to amount to about 1.1 billion EUR per year for the period 2021 to 2027. Some CO_2 infrastructure projects can be supported through CEF, including Northern Lights, but funds from this and other support schemes, including national sources, are considerably below the requirements to realize the currently planned projects (further discussed below), let alone financing of large scale up of projects.

Some detail on EU strategies to realize the EGD targets have recently been published. “A New Industrial Strategy Europe” came in March 2020. The strategy addresses the need for industrial transformation in light of the ambition of a climate neutral Europe but does not contain much in terms of concrete policy proposals. However, it points to several upcoming sector-specific strategies and initiatives that could be important for CCS deployment in European industry. In line with statements in the EGD, the strategy stresses the need to create new markets for climate neutral and circular products but fails to suggest any regulatory measures in support of this.

The hydrogen strategy, due for publication in July 2020, will probably offer more concrete policy instruments with direct relevance for CCS. From earlier, leaked drafts it appears that hydrogen will be considered a priority in EGD and that green hydrogen is to be pursued as the preferred long-term solution, and with blue hydrogen playing and important role in a “transitional phase”. In the leaked draft, retrofitting of existing hydrogen production facilities based on fossil fuel with CCS is mentioned as part of the strategy towards 2030. Furthermore, the draft suggests a support scheme in the form of a carbon contracts for difference (CCfD) to cover the difference between the EUA price and the price level needed to realise hydrogen projects. A pilot version of such a scheme is suggested to incentivize emissions from existing hydrogen production in the industries. The proposal for a CCfD scheme, if retained in the final version of the hydrogen strategy, could become the most tangible and important measure to date in support of CCS deployment.

Policies and plans at the national level of nine countries

A review of national policies of nine countries show that CCS is a part of most national plans for achieving net-zero emissions, with recently increased interest from some countries. Several countries lack storage opportunities and would require storage in another country. Few countries have national support schemes in place.

Policies and plans formulated and implemented in EU member states are key for the short- and medium-term direction of CCS with relevance for the Norwegian full-scale CCS project. In this analysis, the policies and plans of nine countries have been reviewed: Belgium, Denmark, Finland, France, Germany, Ireland, the Netherlands, Sweden, and the United Kingdom. The countries differ in the structure of emissions, abatement strategies and conditions for geological CO_2 storage.

The United Kingdom emphasises CCS as a key decarbonisation strategy and sets targets for CCS deployment in 2030 and 2050. National financing instruments are in place and the storage potential for CO_2 has been mapped. The Netherlands also prioritizes CCS, national financing instruments are in place and an additional CO_2 tax is proposed. The Netherlands has significant storage capacity in depleted gas fields, but timelines and legislation could make storing in the Netherlands uncertain. Sweden’s ambition is to achieve net-zero emissions in 2045 and sees CCS as a measure which could contribute. With high shares of biogenic CO_2 emissions from Swedish energy and industry sectors, the focus is on bioenergy with CCS and Norwegian storage is attractive. An official report has suggested a national support scheme for bioenergy with CCS, but a decision is pending. France has targets for CCS in 2050, though no national support schemes are currently in place or planned. France has the opportunity for onshore storage, but some industrial actors are planning for storage in Norway in the shorter term. Denmark has relatively small emissions from the most relevant industrial sectors but has recently planned significant funds for CCS in the years toward 2030. Denmark also has a large storage potential. Belgium appears to be favourable towards CCS but has no national support mechanisms in place and little storage potential. Some developments appear to be driven from the projects rather than by policies. Ireland recognizes the necessity of CCS to reach its targets and has identified available storage capacity in depleted gas fields in the late 2020s.

Finland and Germany are notable exceptions when it comes to interest for CCS. Finland has not mentioned CCS in its national energy and climate plan. Finland plans on phasing out fossil fuels and relying on natural carbon sinks to achieve net-zero emissions. Finland does, however, have some potential for CCS, especially if biogenic CO_2 emissions are included. Of the investigated countries, Germany stands out with large industrial emissions but little stated interest in CCS. Storage possibilities in Germany are limited due to a ban on onshore storage. There is however some interest from industry, and a large potential for capture.

The country-level analysis indicates that interest for CCS has increased recently. Several countries have taken steps forward in their plans and instruments for CCS, particularly in industry. The few countries who focus on CCS from power generation focus on biogenic CCS. Only a few countries have national support mechanisms in place for CCS, and projects in most countries are therefore heavily reliant on EU funding to move forward.

The current status of relevant CCS projects

The CO_2 volume of CCS projects currently under planning amounts in total to between 20 and 60 $MtCO_2$ before 2030. The CO_2 volumes from the planned capture projects is larger than the planned capacities for storage. Many projects and large volumes of CO_2 have Northern Lights as targets for storage. However, the current level of carbon pricing (ETS and taxation) and financial support schemes falls way short of being adequate to secure investment decisions for all these projects. The scale and timing of project implementation is therefore highly sensitive to EU and national policies and measures in support of CCS deployment.

To assess the near future developments of CCS, we have collected information on planned and possible projects in Northern Europe (not including Norway). A total of 41 potential CCS projects have been reviewed, of which 11 are planning transport and storage at Northern Lights while 8 projects plan to develop their own storage. It is interesting to note, however, that several of the latter have indicated that they might require the use of Northern Lights solution as a back-up for the start of operation and in case the storage preliminary identified turns out to be not as promising as expected. Finally, we have identified an additional 22 less mature, but possible projects which prospectively could store captured CO_2 volumes at Northern Lights.

From the project plans and timelines, Northern Lights storage appears to be in high demand. In interviews, the facilitating effect of Northern Lights was emphasised by nearly all of the capture projects. If all of the projects which aim to store at Northern Lights are realised as planned, the initial Northern Lights capacity of 1.5 $MtCO_2$/y would be filled up from start of operations in 2024, while the capacity of 5 $MtCO_2$/y, planned for the next phase, would be filled up from 2026.

However, all the identified projects are likely to require public funding in lack of a sufficient price of emissions. The availability of public funding represents an important uncertainty related to both scale and timing of the projects. While some of the projects could receive substantial funding through national schemes, most of the projects depend on financing from EU mechanisms such as the Innovation Fund and CEF. At the time of writing, the first call of the Innovation Fund is not yet published, let alone is the first round of support granted. It is impossible to assess the share of funding that would be granted to CCS projects, as it depends the competition against other relevant technology projects. A rough estimate, based on a number of assumptions, is that CCS projects with capacity of between 1 and 3 $MtCO_2$ could be supported on an annual basis from the Innovation Fund and CEF combined. Assuming project commissioning 4 years after an investment decision is made, between 7 and 21 $MtCO_2$ CCS projects could be supported by EU funding mechanisms in 2030.

To investigate the likelihood of EU funding for projects planning to use Northern Lights compared to the likelihood of other projects, we have assessed the sectors, countries, stage of development, “Project of Common Interest” participant and distance to coast. According to these uncertain calculations, EU-funding could support projects with capture volumes equivalent to the rest of phase I capacity quickly, and phase II capacity before 2030. Since EU funding covers only up to 60% of the eligible costs of those projects, this does not necessarily mean that the projects will be realised. The remaining costs would have to be covered by other public financing incentives or private investment. It follows from this that developments in EU and national policies, particularly in the short and medium term and in relation to the 2030 target, are of crucial importance for the scale and timing of project implementation of the reviewed projects.

Assessment of benefits of the Norwegian full-scale CCS project

More ambitious emission reduction targets call for new and more forceful policy measures and have incited planning of many CCS projects. The Norwegian full-scale CCS project is an early mover and as such is in a unique position to impact on the timing and scale of projects being implemented elsewhere and to demonstrate the viability of CCS in a way which can influence policy making. This in turn can provide increased scale of CCS deployment and offer additional learning and cost reductions. The prospects for related Norwegian industrial development are also improved by more ambitious climate targets and policies.

The benefit assessment is made with reference to the following categories:

1. *Demonstration values* which can spur investment decisions and policy decisions in support of CCS deployment
2. *Productivity gains* brought about by technology improvement and cost reductions following from scale in CCS deployment. This effect is closely linked to and depends on effective demonstration.
3. *Value of stored emissions* which is closely related to the “willingness to pay” for emission reductions created by climate polices and regulations
4. Effects for *Norwegian industrial development*

The Norwegian full-scale CCS project can impact CCS deployment both directly, by inciting other investment decisions, and indirectly, through influencing the design and implementation of policies and regulations conducive to CCS deployment. This effect stems primarily from the demonstration value referred to above. The demonstration value has different components: i) it can improve the acceptability and support for CCS as a safe, feasible and attractive abatement option ii) it can offer learning with respect to regulatory and commercial frameworks in support of CCS.

As detailed in this study, European climate polices is at a formative stage, with new and more ambitious targets firmly established, but with many still undecided policies and regulations with impacts on CCS deployment. Further, it has been documented that many CCS projects are under planning, but final investment decisions are yet to be made. In light of these developments, it is our assessment that the potential demonstration value of the Norwegian full-scale CCS project is significant. Specifically, the Northern Lights project offers a secure and viable solution to storage which very soon can demonstrate results with implications for further investment decisions and policy making throughout Europe.

Productivity gains follow from the scale of future CCS deployment. It is likely that the scale will increase in response to EGD and other policy initiatives, and by the actions of an increasingly active industry. Within the next 30 years, over 700 large facilities in the EU will have to undertake massive investments in new technologies and processes to achieve the goal of a net-zero 2050. As we have seen in chapter 2, CCS is a key solution in certain sectors and holds a significant potential as part of low-carbon hydrogen production. The Norwegian full-scale CCS project can, through the demonstration value, impact how early this process starts, and through productivity gains, impact the total cost of transition to carbon neutrality by 2050.

The potential benefits in relation to Norwegian industrial development range across the entire CCS value chain and the full-scale project is likely to increase the competitiveness of the industrial actors involved. Increased ambitions of the EU and member states increase the likelihood and level of CCS deployment and, hence, the market potential. Increased deployment also enhances the future value of Norwegian storage resources. The value of these resources is likely related to increased competitiveness from being an early mover and the reduced cost of storage from scaling effects. Other beneficial effects on industrial development could be related to the value of Norwegian natural gas resources. The heightened ambitions of the EU are likely to reduce demand for natural gas without CCS. Natural gas could have an increased role if used for blue hydrogen production. However, the potential for blue hydrogen production is highly dependent on future policies and therefore uncertain. The full-scale project could contribute indirectly to increased blue hydrogen production by being an early mover, by providing CO_2 transport and storage opportunities.

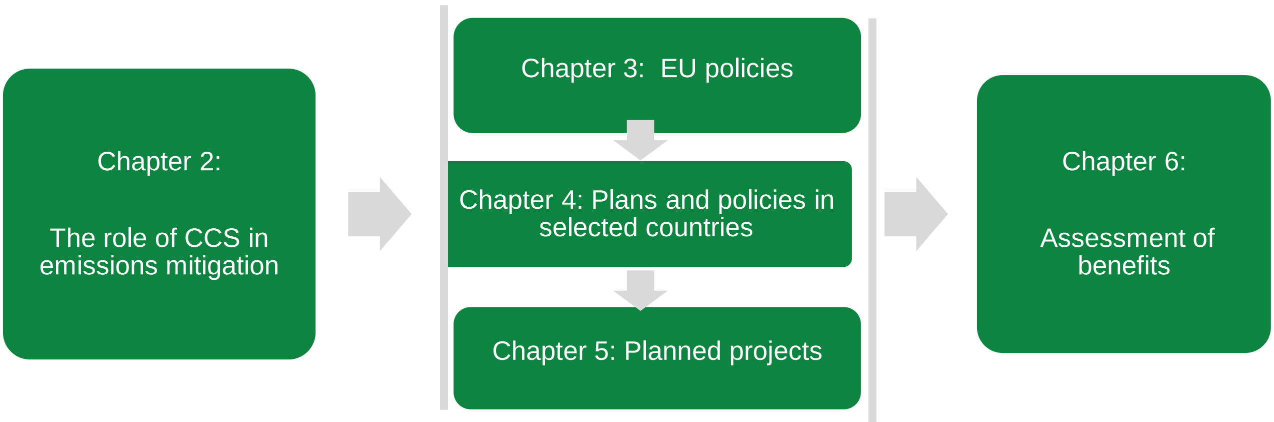
1. Introduction

A number of studies and evaluations have been conducted in preparation for a political decision on support for full-scale carbon capture and storage (CCS) demonstration projects in Norway. The Norwegian Government has stated that the basis for an investment decision will be presented to the parliament (Stortinget) in the fall of 2020. The parliament is expected to address the issue this fall as part of the resolution of the State Budget for 2021. The information and analysis of the report presented here is in preparation for that process.

The report explores how policies in Europe related to the challenges of climate change might impact on the benefits of the full-scale CCS project. The Norwegian project consists of three distinct parts: carbon capture at a waste incineration plant[1] and a cement production plant[2], and a transport and offshore storage project[3]. The three parts are related but are undertaken by three separate industrial entities and are as such subject to their own planning processes and decisions, albeit jointly dependent on Norwegian governmental support.

The analysis presented in this report has consisted of five specific tasks. The results and information gathered under each of the tasks and conclusions drawn are presented in five consecutive chapters of the report (chapter 2 to 6).

Figure 1 – Overview of the project



Chapter 2 explores the potential role of CCS in six sectors: Metals, Minerals, Chemicals and Petrochemicals, Refineries, Waste-to-Energy and Power Generation. In addition, hydrogen production is covered with emphasis on «blue hydrogen" produced from natural gas with a CCS solution. The possible scale of CCS within each segment are estimated and the location of relevant CO_2 sources are mapped. The abatement options at hand and their costs and competitive position are assessed, which in turn form the basis for evaluation their respective responsiveness to policies and regulations.

Chapter 3 reviews the role of EU energy, industry and climate policies and their potential impacts on CCS deployment. Obviously, the new ambitious targets for emission reductions of European Green Deal can be decisive for CCS, but major uncertainties remain over the relative importance of different policy instruments imposed at the EU level. Moreover, the trajectory for emissions, and specifically the

[1] https://www.fortum.com/reducing-co2-emissions-carbon-capture

[2] https://www.norcem.no/en/CCS

[3] https://northernlightsccs.com/en/about

reduction target for 2030, is uncertain and may be particularly important for the benefits of the Norwegian full-scale project. The chapter includes a review of the most relevant policy instruments and a discussion of their potential role and an overview of pathways which have been presented for CCS deployment based on different scenario assumptions.

Chapter 4 includes a review and analysis of carbon capture potentials and related plans and policies for CCS and hydrogen production in selected countries. Nine countries of interest for the Norwegian full-scale project have been chosen for this analysis. For each country, an assessment of their potential contribution to the full-scale project benefits has been made based on criteria such as: i) governmental position on CCS ii) capture potential iii) CCS deployment timeline iv) interest for storage in Norway.

Chapter 5 focuses on relevant projects which are at a planning stage. A summary of potential CO_2 from the projects, their location and need to storage capacity are presented with further details for individual projects being presented in an annex to the report. This chapter also includes some tentative results from an analysis of financial support requirements for the reviewed projects based on stipulated abatement costs and the carbon pricing incentives which might result from the ETS and energy/CO_2 taxation.

Chapter 6 assesses to what extent the increased ambition levels affect the benefits of the full-scale project and explore some of the main benefits, under four broad categories: the demonstration effect, the value of CO_2 stored, productivity benefits and industrial development.

2. The role of CCS in emission mitigation

In 2017, greenhouse gas emissions from EU 28 countries totalled 4.3 GtCO_2e. Land use, land use change and forestry contributed to negative emissions of about 261 MtCO_2e, leaving net EU emissions at about 4 GtCO_2e. With the European Green Deal, a target of net-zero emissions in 2050 has been set. A wide range of climate mitigation measures in all sectors will be necessary to achieve this target.

Box 1 - CCS and CCU

CCS and CCU

Carbon Capture and Storage (CCS) is a technology that allows to reduce emissions from large CO_2 sources. It consists of 3 elements:

- capture at a facility of CO_2 from flue and process gas,
- transport to a storage site via pipeline or ship (for smaller volumes, barges, trucks and trains can be envisaged), and
- injection of the CO_2 in an underground geological formation (deep saline aquifers or depleted oil / gas fields).

The cost of CO_2 capture depends on the volume of gases to treat, its pressure and the CO_2 concentration. Some processes therefore have higher capture costs than others. While high purity CO_2 streams are less costly to capture, some streams with low volume, low pressure and/or low concentrations could lead to very high capture costs. Storage location is also key in the cost assessment as it will drive the cost of the transport and storage part of the chain.

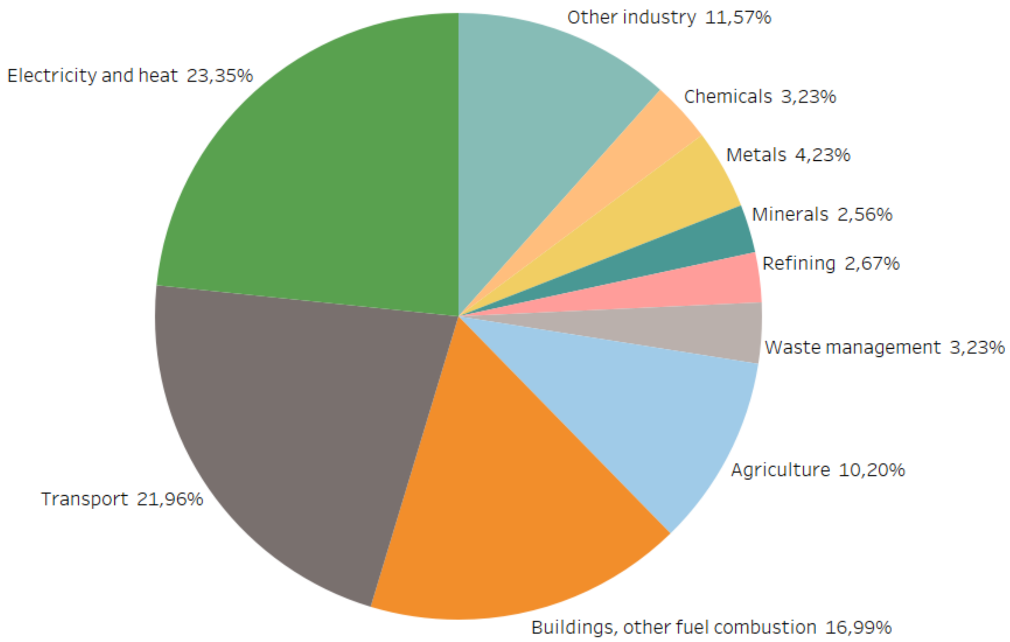
In addition, CCS chains can benefit from economies of scale and concepts with single source capture to single CO_2 storage could be less cost effective than a clustered approach.

Carbon Capture and Utilization (CCU)

Captured CO_2 can also be used. For usage purposes, it can either be used directly (for enhanced oil recovery, in the food and beverage industry and as a refrigerant) or converted to other products through chemical, biological or physical processes. Carbon Capture and Utilization may play a role in decarbonizing industry depending on the CCU process, on the availability of low carbon energy and on the reference process emissions. Emissions reductions achieved through CCU should be studied on a case-by-case basis. Long-term storage of CO_2 in e.g. building materials could be a relevant solution in the long run.

While a large share of emissions come from dispersed small sources (e.g. residential heating, transport) which are not currently considered relevant for carbon capture and storage, a significant share of emissions come from large point sources (industry, power and heat), where it can be applied (50.8% of the overall EU 28 emissions). For the smaller point sources where hydrogen could play a role (transport, building emissions), CCS can be applied indirectly for producing blue hydrogen (hydrogen from steam methane reforming with CCS). Hydrogen usage can also be relevant for emission reductions from a range of industrial large point sources, as it is detailed in the next paragraphs.

Figure 1 - EU 28 GHG emissions in 2017, by sector



Source: Eurostat

In different scenarios of what a net-zero European future could look like, the importance and role of CCS varies widely. Technically, CCS could play a very large role. However, depending on sector and process, a range of other options are also available. These other mitigation options have abatement costs which are both higher and lower than CCS. Different combination of future technology developments, policies and economics can lead to very different pathways. This chapter investigates the mitigation options for the sectors that are most relevant for CCS, assessing the competitiveness of relevant abatement options in each sector, including CCS.

In the sector assessment, we start with the end users of energy, i.e. the metals, minerals and chemicals industries. These are traditionally considered hard-to-abate sectors. Emissions are a result of both energy usage and processes.

Some abatement options involve using fossil-free energy carriers such as electricity, hydrogen, biomass. Increased use of these energy carriers require increases in production or transformation earlier in the energy flows. To avoid migration of emissions to the transformation stage, these increases must also be mitigated, e.g. using renewables for electricity production or CCS on hydrogen production. The transformation sectors, electricity and heat production, waste-to-energy, refining, and future hydrogen production also have a range of mitigation options for reduced emissions, including CCS. Bioenergy can be used both in energy production and as a feedstock in industrial processes. CCS associated with bioenergy is one of the few technologies that can lead to negative emissions.

Furthermore, reduced emissions through increased circularity is a potentially important abatement option. Recycling of minerals, chemicals, and metals could significantly reduce emissions from production. Circularity also has an effect earlier in the energy flows - recycling of metals decreases the need for energy, while recycling of plastics reduces the need for refining and for waste incineration. The potential of circularity must therefore be assessed in combination with other abatement measures.

In this chapter, the abatement options in the sectors identified, their relative abatement costs, and their potential effect on demand for increased electricity or hydrogen production are summarized. This lays the ground for further analysis in the following chapters, which assess the development of CCS as a result of EU and member state policies and project plans.

Box 2 - Abatement costs

Abatement costs

In this report, the abatement costs presented have been compiled from other studies. The assumptions behind these numbers are not detailed in the reports (short-/long-term cost, technology development assumptions, economic assumptions etc.). This makes the comparison of abatement options and costs in the different sectors challenging and results in large range of uncertainties for the role of CCS in each sector. Some studies, such as *Industrial Transformation 2050, Pathways to net-zero emissions from EU heavy industry*, published in 2019 by Material Economics, have presented abatement costs for multiple measures which are comparable within and between sectors. When available, these are given more weight in this report to illustrate the relative costs of different abatement measures.

Box 3 - Capturable volumes

Capturable volumes

The term “capturable CO_2 emissions” is used in this report to describe the amount of emissions which could be captured from a technical-economic perspective. Some emission shares are not economically feasible to capture on an industrial site. Capturable emissions represents the abatement potential factor of CCS (applicability times reduction efficiency).

For each emission source *i*, the abatement potential is estimated based on the following equation:

$$Abatement\ Potential_i = Emission_i * Applicability\ of\ the\ technology_i * Reduction\ efficiency\ _i$$

where

The applicability of the technology (in %) represents the share of the total emissions from an emission source to which the abatement technology can be applied.

Reduction efficiency (in %) represents the percentage of technically achievable emissions reduction for an abatement technology, after it has been implemented.

In industrial facilities CO_2 can be emitted through one or several stacks, depending on the process. Capture is not considered feasible on some stacks, since they either do not emit enough CO_2 or they have low CO_2 partial pressures (CO_2 concentration times pressure of the flue gas). Clustering emissions could be possible, but it might still be technically difficult or not economic to capture from all sources. Both factors (flowrate and partial pressure) will impact the capture unit cost: lower factors give higher unit cost. Generic sector-specific factors are used to account for this aspect to have a rough idea of what could be captured for each sector.

Sector	Capturable volume *Range of values given by the experts / found in publications*	Capturable volume *Value considered in the assessment*	Comments from experts
Power plant (Coal, biomass, oil, gas fired)	90%	90%	
Steel plant	30% (just on Blast furnace – Top Gas Recycling will reduce further the emissions by 50% - 80%) (3 sources)	60%	2 experts mentioned 60% and 1 40% 30% (just on Blast furnace – Top Gas Recycling will reduce further the emissions by 50%) - 80% (3 sources)
Cement	70-90%	90%	The low value is to account for the fact that it might not be applied everywhere
Refinery / Petrochemical	50%-70%	45%	70% at high costs
Chemical	50%-80%	50%	Very different from one industry to the other – potential high purity sources
Ammonia	50-90%	50%	
Waste-to-Energy	90%	90%	

References: Experts interviewed from IFP EN / SINTEF ER / DNV GL / VTT / Chalmers
CSLF, Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs) - From Energy/Emission Intensive Industries to Net-zero Emission Industries, draft report – July 2019

2.1 Metal production

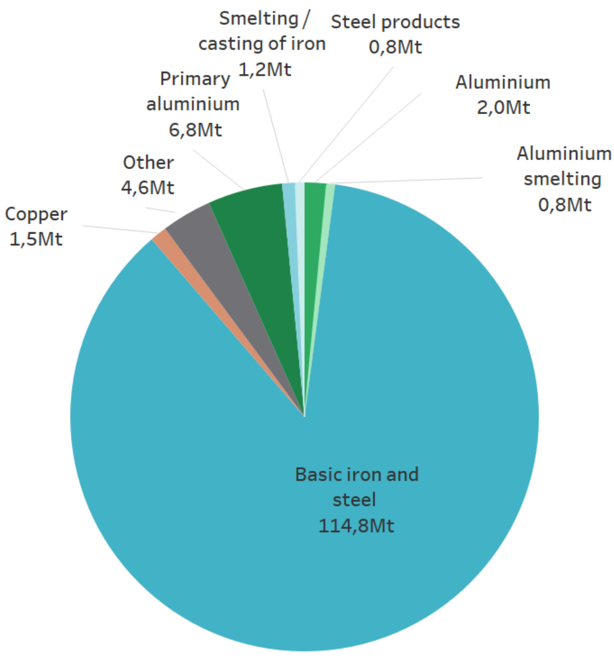
Metal production is an important industrial sector in the European Union. The metal manufacturing industry can be split into two distinct sub-sectors: the production of ferrous metals and of non-ferrous metals. Ferrous metals mainly refer to iron and steel production while non-ferrous metals include mainly aluminium, copper and zinc. The products from these two subsectors provide essential raw material for a wide variety of other strategic sectors such as automotive, aerospace, construction, electronics, medical devices, etc.[4]

In 2017, 168,000 kt of steel were produced in the European Union, with Germany and Italy as the largest contributors (43,000 kt and 24,000 kt, respectively).[5] As far as the other types of metal production are concerned, 4,200 kt of aluminium were produced in the EU and the EFTA in 2016[6] and copper production that same year in the EU was of 2,600 kt[7].

2.1.1 Sector emissions and plans

The metal production segment represents about 182 $MtCO_2e$[8] of GHG emissions in 2017 of which 132 $MtCO_2$ from large stationary sources (above 100 $ktCO_2/y$).

Figure 2: CO_2 emissions from the metal industry in 2017 – Large stationary sources (>100 $ktCO_2/y$)



Source: Data: E-PRTR / Carbon Limits Analysis

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[4] European commission, *Metal industries,* https://ec.europa.eu/growth/sectors/raw-materials/industries/metals_en

[5] Eurofer, *Crude steel production – all quantities,* *http://www.eurofer.org/Facts%26Figures/Crude%20Steel%20Production/All%20Qualities.fhtml*

[6] European Aluminium, *Current primary production,* https://european-aluminium.eu/data/economic-data/current-primary-production/

[7] European copper institute, *The structure of Europe's copper industry,* https://copperalliance.eu/about-us/europes-copper-industry/

[8] Eurostat, *CO_2 emissions per sector*

Iron and steel production represent the vast majority of emissions from the EU metal industry. Emissions from aluminium, the second largest subsegment, is about 5% of the industry's emissions. Copper, ferroalloys, lead, and zinc production all have smaller shares.

The European iron and steel industry is significant, both in number of production facilities and emissions. Throughout Europe, 67 basic iron and steel facilities emitted 115 MtCO_2 in 2017[9]. Even if challenged by international competition, the industry expects production to grow and level off at around 190 Mt in the 2040s.[10]

There are 22 aluminium production facilities in the EU, emitting about 8.8 MtCO_2/y. Aluminium is primarily produced through alumina electrolysis, which has associated carbon emissions from carbon in the anodes. Due to low CO_2-concentrations, it is relatively costly to apply CCS on emissions from aluminium production. Some research has explored the possibility of achieving higher CO_2 concentration through redesign of production processes, but this research is still at early stage. In addition, the industry is developing other carbon free production routes.[11] Due to this, and the relatively low emission levels in the EU, we do not investigate aluminium further.

There are only 4 copper plants with large emissions in the EU, together emitting about 1.5 MtCO_2/y. Copper production involves smelting and electrolytic refining to convert concentrates, imported intermediate materials and end-of-life scrap into copper metal. Due to a limited number of facilities and low levels of emissions, we do not investigate copper production further.

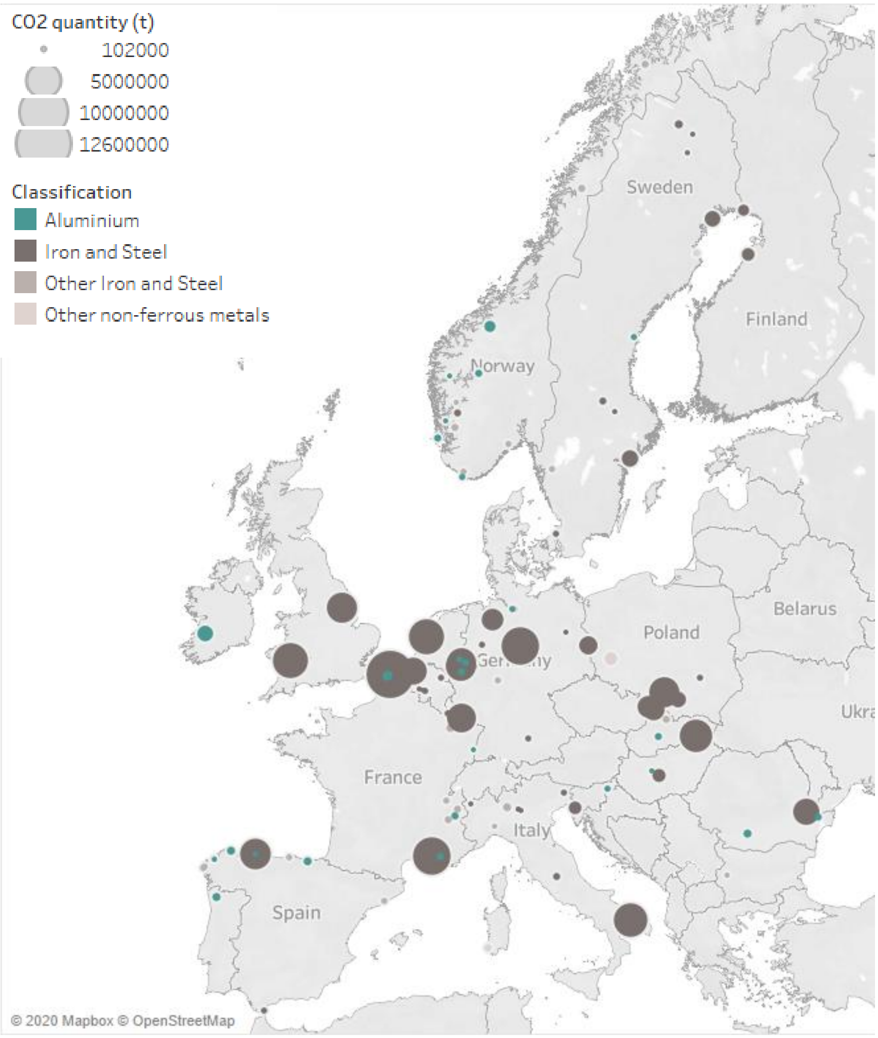
The locations of metal production plants in Europe and their CO_2 emissions are shown on Figure 3. Among the metal producers, iron and steel facilities are emitting the most per facility (1.9 MtCO_2/y on average). A high concentration of these facilities are around the North Sea.

[9] Eurofer, *Low carbon Roadmap – Pathways to a CO_2-neutral European steel industry,* 2019

[10] Material Economics, *Industrial Transformation 2050 – Pathways to net-zero emissions from EU heavy industry,* 2019

[11] See for example https://www.elysis.com/en

Figure 3: Location of metal production plants in Europe and CO_2 emissions in 2017 for plants emitting more than 100 ktCO_2/y



Source: Data: E-PRTR / Carbon Limits Analysis

Basic iron and steel is produced mostly through the *Blast Furnace – Basic Oxygen Steel* process but electric arc furnaces are also used (24% of the production) and *Direct Reduction Iron* as well (5% of the production). The Blast Furnace – Basic Oxygen Furnace process requires a series of units: blast furnace stoves, coke oven stacks, flares and minor users, hot strip mill stacks, lime kiln stacks, and sinter plant stacks. Emissions are associated with each of these processes, with European emissions at about 1.9 tCO_2 per tonne of virgin steel. A high share of scrap iron and steel is recycled and reprocessed in electric arc furnaces.

In 2019 EUROFER, the iron and steel industry association, presented a roadmap toward a low carbon European iron and steel industry. The roadmap has different potential scenarios considering economic feasibility, technical developments and regulations. With current policies, the industry has estimated that only 15% of emissions could be reduced in an economic way by 2050. Deep emission reductions of up to 95% would require deployment of new technologies, including CCS and hydrogen.[12] The investment requirements were estimated to be approximately EUR 52 billion.[12]

[12] Eurofer, *Low carbon Roadmap – Pathways to a CO_2-neutral European steel industry,* 2019

2.1.2 Available abatement measures

Both carbon capture and hydrogen are possible abatement measures in the sector. To provide deep emission reductions with either CCS or hydrogen, significant changes to the production methods must be applied.[13] The abatement cost estimates are highly dependent on the prices of hydrogen and electricity. If hydrogen is produced with electricity, high electricity prices will favour smelt reduction using CCS, while low electricity prices favour hydrogen direct reduction.

CCS

Anywhere between 11-71 $MtCO_2$ captured through CCS would be needed to achieve net-zero emissions according to one study, depending on the scenario or technologies considered.[13]

The current integrated steelmaking route involves coke plants and pellet plants for preparation of raw materials, blast furnaces for ironmaking, and basic oxygen furnaces for steelmaking. About 1.9 tonnes of CO_2 are emitted per tonne of steel, where about 1.3 tonnes CO_2 are associated with the blast furnace. CCS can be applied to the blast furnace, and if using recycled exhaust gas, capture could reduce emissions up to 50%.[13] The abatement costs of CCS with the current production technology are in the range of 70 to 95 EUR/tCO_2 (including transport and storage).[14]

One pathway to further reduce emissions using CCS could be to completely change the production process, using direct smelting. Direct smelting could replace multiple processing steps and would result in a higher CO_2 concentration from a single point, which would give cost reductions for carbon capture and reduced energy usage.[15] However, this process, known as Hisarna, has not been deployed in full-scale, and the technology must be demonstrated.

A widespread decarbonisation of iron and steel production using CCS as the main pathway would require 3 times more electricity than today, to a total of 210 TWh.[13]

If it were to be financially viable to them, some steel manufacturers have indicated they could foresee transport and storage of captured CO_2 emissions to Norway for storage.[16] Arcelor Mittal is planning to test the DMX™ CO_2 capture technology in 2022 and a demonstration project is currently being designed for 1 $MtCO_2$/y. If the process is proven to be efficient, it could be deployed on the other Arcelor Mittal plants in Europe.

CCU

Some steel companies, facing strong competition from regions with less stringent environmental regulations, see CCU as a more achievable path for emissions reduction as it can provide potential revenues. The captured CO_2 could then be used for chemical production, such as methanol, ethanol, or naphtha. Depending on the volumes and prices, CCU could potentially enable CCS when storage becomes more readily available and emissions more costly.[16]

The iron and steel sector has developed several CCU projects with the most advanced ones at a pilot stage. If these pilots are successful, the intention is to deploy the technologies broadly. This will, however, require financial support either from the EU or from member states as, at the moment, CCU-based products are more expensive than their fossil counterparts (e.g. methanol).[16] It is also key to develop some internationally recognized methodologies to assess the mitigation effects of the CCU

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[13] Material Economics, *Industrial Transformation 2050 – Pathways to net-zero emissions from EU heavy industry,* 2019

[14] Naims, H., *Economics of carbon dioxide capture and utilization – a supply and demand perspective,* 2016

[15] The abatement costs of using the direct smelting process when developed, with CCS, was estimated to 36 EUR/tCO_2 by Material Economics.

[16] Interview with ArcelorMittal

technologies as in some cases CCU might not lead to a reduction of CO_2 emissions in the atmosphere.

Hydrogen

Hydrogen used to reduce the iron ore to iron in a direct process is potentially an important abatement measure. Some actors in the steel sector prefer clean hydrogen rather than CCU/CCS as an abatement option. This especially the case in countries where the public opinion towards carbon capture is negative. The direct iron reduction process is already widespread internationally using natural gas. The technology for using hydrogen in this process is under development, with planned demonstration projects. The heat energy to produce steel from hydrogen would then be using electric arc furnaces, which are already used in steel recycling. The direct iron reduction process removes the need for coke ovens and blast furnaces. The abatement cost is highly dependent on the price of hydrogen. For green hydrogen, when the technology is developed, abatement costs have been estimated to be 18-57 EUR/tCO_2, with electricity prices of 40-60 EUR/MWh.[17]

A widespread deployment of the hydrogen direct reduction process would require large amounts of hydrogen, estimated in one study to be 5.5 Mt of hydrogen by 2050. If this amount of hydrogen were to be produced by electrolysis, this would increase demand for renewable electricity by 234 TWh.[18] The electricity demand is estimated to be around 5 times higher than today, 355 TWh/y, due both to hydrogen production and electrification of heating needs, which is about the current annual electricity production from wind in EU 28.[17] Other studies have found significantly higher needs for electricity for iron and steel production based on hydrogen, up to 700-1000 TWh in 2050.[19]

The need for additional decarbonized electricity is high and would require the development of significant new renewable power. Hydrogen from Steam Methane Reforming with CCS (i.e. blue hydrogen) could be used as a transition solution before ensuring that there is enough decarbonized electricity to produce and use green hydrogen in the industry.[20] (see section 2.6)

Other

Increased recycling rates could also reduce production of virgin steel, although the share of steel recycled is already high in the EU at 85%. Recycling steel using electric arc furnaces could provide a cost-efficient alternative for the available scrap steel volumes. Increased steel scrap usage requires improved design of products, better techniques in handling and new metallurgical techniques. Given such improvements, scrap steel could represent about half of EU steel production. [17]

2.1.3 Summary metal

Different combinations of abatement technologies give a range of needs for CO_2 storage to achieve net-zero emissions from the steel sector. A range of 11-71 MtCO_2 could be captured in 2050 in different pathways towards net-zero considering hydrogen reduction, circular economy and CCS. [17]

The different pathways are estimated to demand increased investments in the steel industry of 25-65% until 2050, compared to today's baseline. The circular economy pathway is in the lower range, while

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[17] Material Economics, *Industrial Transformation 2050 – Pathways to net-zero emissions from EU heavy industry,* 2019

[18] Eurofer, *Low carbon Roadmap – Pathways to a CO_2-neutral European steel industry,* 2019

[19] In-depth analysis in support of the Commission Communication COM(2018) 773

[20] Oxford Institute of Energy Studies, *Blue hydrogen as an enabler of green hydrogen – the case of Germany*, 2020

the pathway using a large share of hydrogen represents 60% increase, and the CCS priority pathway represents a 65% increase.

CCS associated to CCU is seen as a key decarbonisation technology for some of the industrial actors while some others see the hydrogen path as essential. The “medium” rating for the role of CCS reflects this difference of opinion. If a hydrogen path is chosen for steel production, CCS could also potentially play a role in the production of hydrogen from natural gas, especially as large volumes of new renewable capacity would be needed for green hydrogen production (see chapter 2.8).

Table 2 - Summary table of iron and steel

Emissions 2017 ($MtCO_2$)	115 (67 plants)
Significance of CCS in decarbonisation	Medium, as hydrogen direct iron reduction is competitive, depending on H_2 price. If blue hydrogen, then CCS is key.
Cost of CCS (EUR/tCO_2) including transport and storage	70-95 (Current technology)
Cost of other abatement options (EUR/tCO_2)	
Hydrogen direct reduction (green H_2)	18-57
Scenario capture volume 2030 ($MtCO_2/y$) to reach a net-zero target by 2050	~5
Scenario possible capture volume 2050 ($MtCO_2/y$) to reach a net-zero target by 2050	11-71
Technical capturable volume ($MtCO_2/y$) – all Europe[21]	69
Role of CCS	**Medium**[22]

2.1 Mineral production

2.1.1 Sector emissions and plans

The mineral industry consists primarily of the manufacture of cement, lime and plaster, ceramics, glass, and mineral fibres. The mineral industry emitted about 198 $MtCO_2e$[23] in 2017, of which 152 $MtCO_2$ are from large stationary sources (above 100 $ktCO_2/y$).

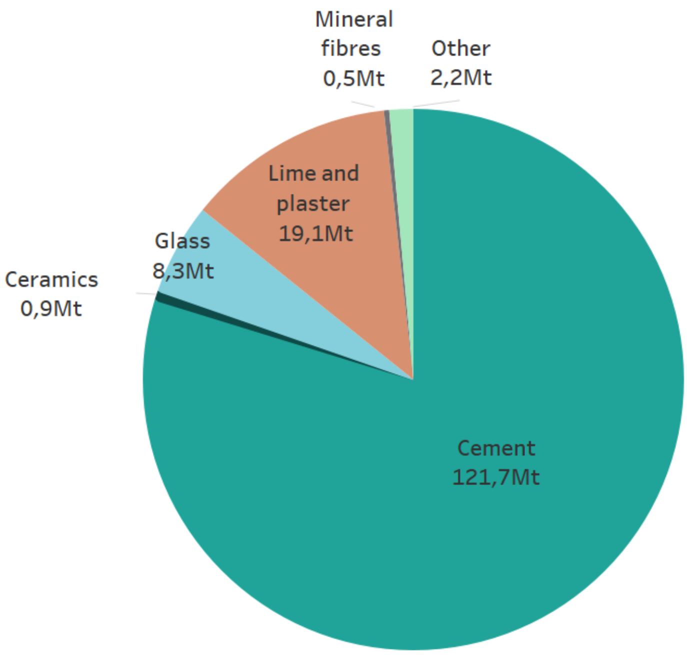
Cement production represents 80% of these emissions, lime and plaster production represents 12.5%, and ceramics production represents 5%. The focus of this section is cement production.

[21] Capturable CO_2 emissions – see Box 3 - Capturable volumes

[22] Indirect use of CCS through blue H_2 production is reflected on in section 2.6.

[23] Eurostat, *GHG emissions per sector*

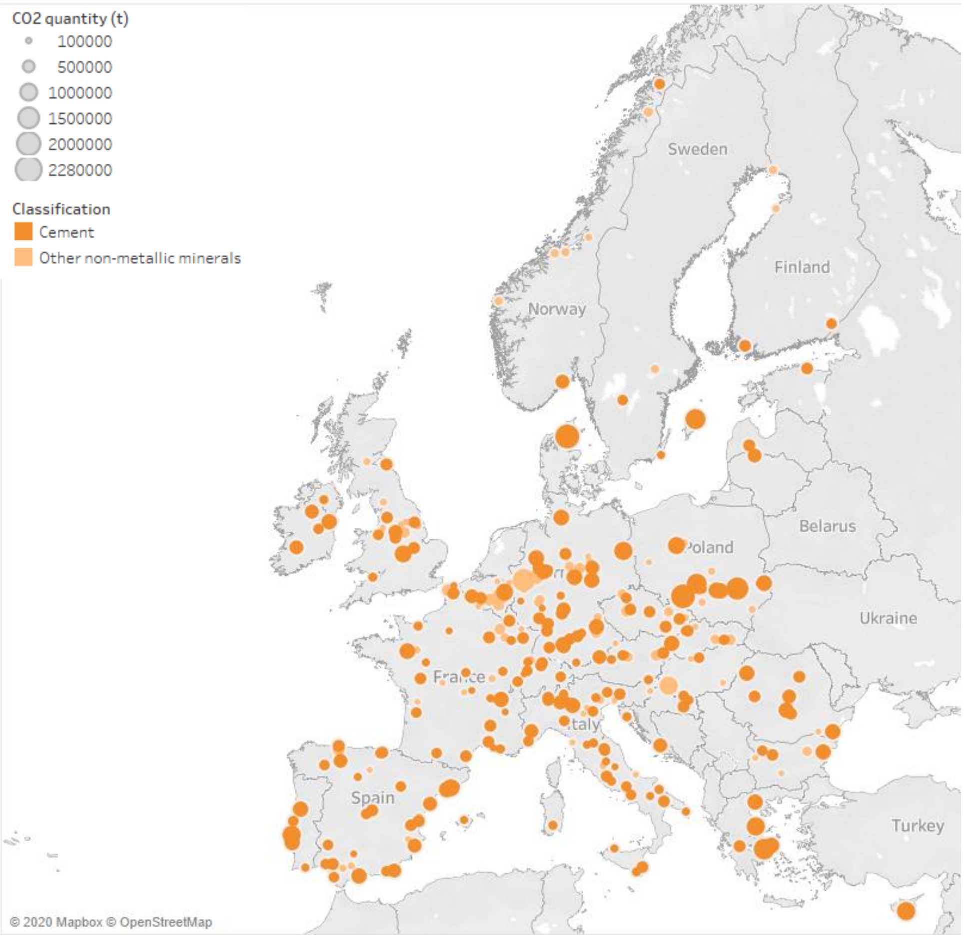
Figure 4: CO_2 emissions from the mineral industry in 2017 – Large stationary sources (>100 ktCO_2/y)



Source: Data: E-PRTR / Carbon Limits Analysis

Cement production facilities are geographically distributed as cement is mostly locally produced and locally consumed. On average, each facility has emissions of 0.6 MtCO_2/y.

Figure 5: Location of the mineral production plants in Europe and CO_2 emissions in 2017 for plants emitting more than 100 ktCO_2/y



Source: Data: E-PRTR / Carbon Limits Analysis

The majority of CO_2 emissions from cement production are from clinker production, specifically CO_2 from calcining limestone and from burning of fuels to heat the kiln. Process emissions (heating of limestone and release of CO_2) represents 60 to 65% of cement manufacturing emissions.

CEMBUREAU, the European cement association has recently published its climate neutrality roadmap[24] with a neutrality objective by 2050 and an intermediate goal at 40% reduction compared to 1990 along the cement value chain for 2030. Material Economics has also looked into the pathways to net-zero emissions from cement production in Europe[25].

The production of 1 tonne of cement in 2017 leads on average to emissions of 691 kgCO_2 along the cement value chain in the EU 28.[24] The production in Europe could increase by 10% by 2050[25] but the emissions were projected to remain at today's levels, due to improvements in energy efficiency and decarbonization of energy inputs.

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[24] CEMBUREAU, Cementing the European Green Deal, May 2020, https://cembureau.eu/media/1948/cembureau-2050-roadmap_final-version_web.pdf

[25] Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry

2.1.2 Available abatement measures

CCS

CCS is key in the cement sector as there are no other ways to reduce the process emissions significantly. While many other sectors have multiple emission sources, post-combustion CCS is a relatively straightforward solution to implement, as on a cement factory there is just one source of CO_2. Oxyfuel and direct separation technology (tested at LEILAC at Lixhe and planned at a 100 ktCO_2/y scale by 2025) can also be used on cement plants.

By 2050, CCS/CCU appear to be the most effective abatement option to reach carbon neutrality along the cement value chain, allowing for an emission reduction of 280 kgCO_2/t cement (2017 emissions: 667 kgCO_2/t cement).[26]

For the deployment of CCS, CEMBUREAU has highlighted the importance of access to public funding for innovation. The association also underlines the urgency for EU to support the development of a CO_2 transportation network. The availability of nearby CO_2 storage has been considered a significant barrier for deployment, and long-distance transport and storage solutions are necessary for the industry to reach is net-zero target. Furthermore the importance of a high CO_2 price was necessary, along with the ability to pass on costs of CCS (estimated from 70% to 115% increase in production cost.[25] The cost impact on buildings built with cement produced with CCS has been estimated to 3%.[27]

No abatement cost is given in the CEMBUREAU document. The abatement costs in the Material Economics report for the cement sector are given in a generic way between 60-89 EUR/tCO_2 with CCS representing respectively 35 and 80% of the emissions reduction. Scenarios developed by Material Economics and CEMBUREAU show a capture volume of 5 to 12 MtCO_2/y in Europe by 2030 and 31 to 85 MtCO_2/y in 2050 (around 50 for CEMBUREAU).

Other

By 2030, the other abatement measures considered by CEMBUREAU at clinker and cement production levels are the following ones:

- Fuel substitution using waste streams and biomass (target: 60% alternative fuels containing 30% biomass)
- Thermal and electrical efficiency and use of renewable electricity
- Use of alternative decarbonated raw materials such as waste materials and biproducts from other industries to replace the use of some of the limestone (e.g. recycled cement paste, waste lime)
- Production of low carbon clinker
- Production of low clinker cements (from 77% to 74% in 2030) through the use of substitutes such as fly ash, natural pozzolans, calcined clays, etc.

In addition, for 2050, CEMBUREAU envisages a very small reduction contribution the use of hydrogen in the clinker production and more use of alternative fuels (2050 target: 90% alternative fuels with 50% biomass) in addition to CCS. The alternatives to CCS can lead to a reduction of 160 kgCO_2/t cement,

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[26] CEMBUREAU, Cementing the European Green Deal, May 2020, https://cembureau.eu/media/1948/cembureau-2050-roadmap_final-version_web.pdf

[27] CSLF, Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs) - From Energy/Emission Intensive Industries to Net Zero Emission Industries, draft report – July 2019

which compared to 2017 emissions (667 kgCO_2/t cement)[28] would represent a 24% reduction. These measures alone will not be sufficient for the cement industry to achieve the targeted reductions.[29] Material Economics envisages the same measures but considers CCS to have a larger role in 2030.

Box 4 - Opportunities in the lime and glass industry in EU

Opportunities in the lime and glass industry in EU

The European Lime Association and Glass Alliance Europe have both identified CCUS as one of the required abatement solutions to be climate neutral.

For lime, CCS represents the deepest emission cuts as process emissions in the lime sector amounts to 68% and the other abatement measure are focused on the heating part of the process (fuel switching, energy efficiency).

In glass production there are some process emissions (15/25% of the emissions) where CCS/CCU is relevant. The other measures are targeted towards low carbon combustion through the use of among other things hydrogen.

Both industries are unlikely to be first movers as they have small units, not necessarily located close to a storage site. They could join an existing CCS project if located close to a hub or an appropriate storage site in 2040-2050.

References: Glass Alliance Europe, The European glass sector contribution to a climate neutral economy, position paper, 2019.
European Lime Association /Ecofys, A competitive and effective lime industry, cornerstone for a sustainable Europe, 2014

[28] CEMBUREAU, Cementing the European Green Deal, May 2020, https://cembureau.eu/media/1948/cembureau-2050-roadmap_final-version_web.pdf

[29] CSLF, Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs) - From Energy/Emission Intensive Industries to Net Zero Emission Industries, draft report – July 2019

2.1.3 Summary minerals

Table 3 - Summary of minerals (cement)

Emissions 2017 ($MtCO_2$)	122 (206 plants)
Significance of CCS in decarbonisation	High. Key technology with few other options
Cost of CCS (EUR/tCO_2)	60-89 100-120[30]
Scenario capture 2030 ($MtCO_2/y$)	5-12
Scenario capture 2050 ($MtCO_2/y$)	31-85
Technical capturable[31] volume ($MtCO_2/y$) – all Europe	109
Role of CCS	**High**

2.2 Chemicals/Petrochemicals

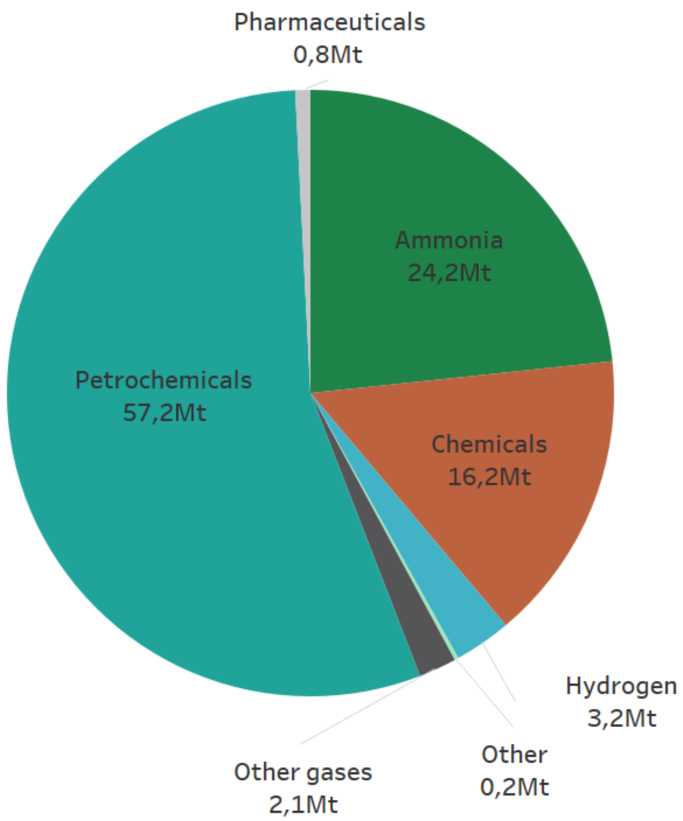
2.2.1 Sector emissions and plans

The chemical and petrochemical industry covers complex value chains closely related to other sectors. Production of chemicals and petrochemicals in the EU represented about 135 $MtCO_2e$ of GHG emissions in 2017. About half of the emissions are from fuel combustion and the other half are process emissions. Further breakdown by subsectors are shown in Figure 4. Emissions from large petrochemical plants represent 57 $MtCO_2$, which manufacture plastics, organic and inorganic basic chemicals. Emissions from chemical plants, which manufacture inorganic and organic chemicals and chemical products, represent 16 $MtCO_2$. Ammonia production from large facilities represents 24 $MtCO_2$ and hydrogen 3 $MtCO_2$ in 2017.

[30] Naims, H., *Economics of carbon dioxide capture and utilization – a supply and demand perspective,* 2016

[31] Capturable CO_2 emissions - See Box 3 - Capturable volumes

Figure 6: CO_2 emissions from the chemicals/petrochemicals sector in 2017 – Large stationary sources (>100 ktCO_2/y)



Source: Data: E-PRTR / Carbon Limits Analysis

Ammonia is primarily an input for fertilizer production, but is also used in various other industrial applications. Ammonia is produced by combining hydrogen with nitrogen. The hydrogen used is primarily produced by steam methane reforming of natural gas. On average, each tonne of ammonia produced in the EU represents 1.8 tCO_2 emissions.

A large share of petrochemicals production has plastics as the end product. Naphtha refined from crude oil or ethane from natural gas is used as feedstock. Steam cracking and polymerisation are associated with emissions using today's processes. Per tonne of plastic production, 0.2 tCO_2 are emitted in the refining process, 0.9 tonnes from the cracking process, 0.6 tonnes from polymerisation and blending.[32]

Chemical and petrochemical plants are primarily located in Germany and France, Belgium. Ammonia and hydrogen plants have average emissions of respectively 1 and 0.3 MtCO_2/y, while petrochemical and chemical plants emit respectively on average 0.6 and 0.3 MtCO_2/y.

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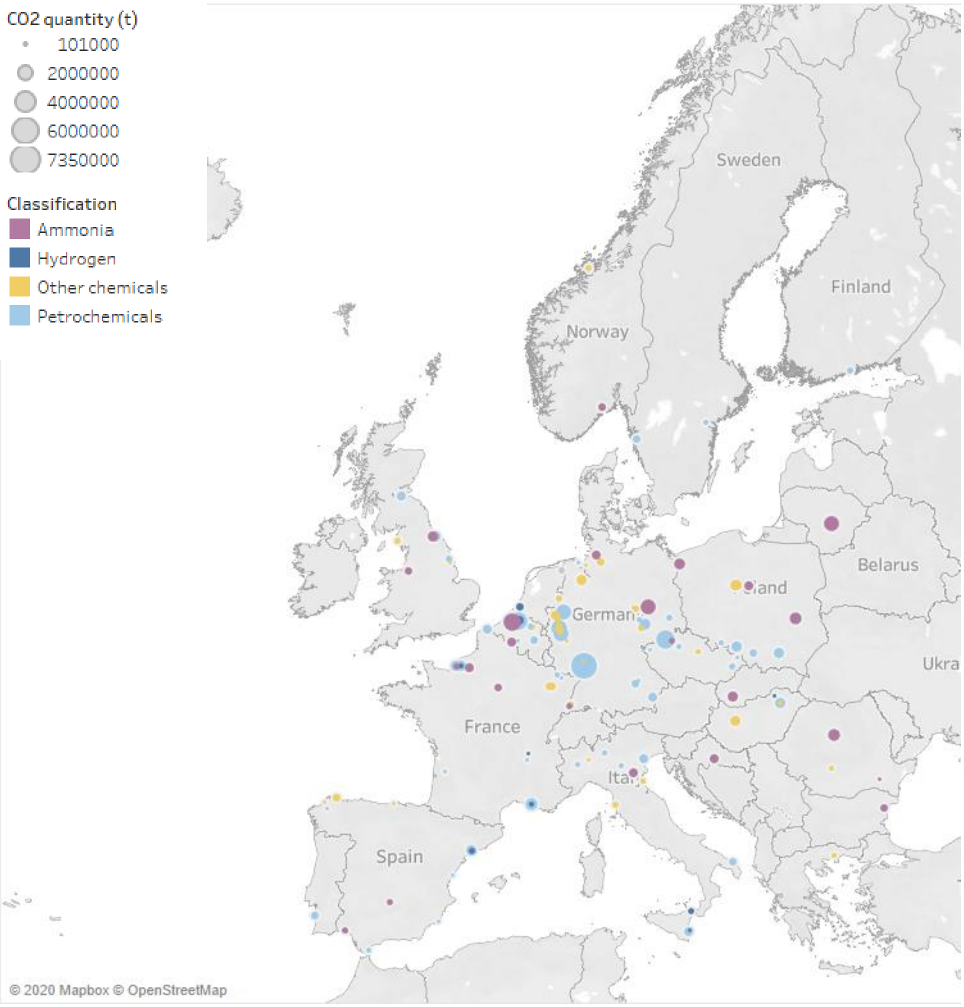
[32] In addition, end of life emissions from waste incineration contribute to a large share of life-cycle emissions. End of life incineration emits 2.7 tonnes CO_2 per tonne of plastic.

Figure 7: Location of the chemical / petrochemical production plants in Europe and CO_2 emissions in 2017 for plants emitting more than 100 $ktCO_2/y$



Source: Data: E-PRTR / Carbon Limits Analysis

2.2.2 Available abatement measures

Both CCS and other mitigation options are available for chemicals and petrochemicals.

CCS

CCS can be applied to process emissions as well as emissions from fuel combustion. In a roadmap from 2013[33], the industry assumed that depending on process, between 75% and 90% of emissions from fossil fuels could be captured and stored, given that barriers related to public acceptance, infrastructure were resolved. Depending on policy and production scenarios towards 2050 and assuming increased production, between 0 and 30% of the emissions were projected to be captured and stored from the sector by 2050 (around 0 to 30 $MtCO_2/y$).

For ammonia production, steam methane reforming of hydrogen results in a high purity stream of CO_2, and capture is therefore easier compared to most other emission streams. Ammonia is typically produced at larger sites with about 1 $MtCO_2/y$ of emissions, with almost a pure stream of CO_2. A

[33] CEFIC / Ecofys, European chemistry for growth - Unlocking a competitive, low carbon and energy efficient future,2013.

smaller share of emissions also results from the heating process, which have lower concentrations, to deeply reduce emissions, either electrification of the heating source or CCS on combustion flue gases must be put in place. According to Material Economics, a CCS pathway of ammonia production could capture 17 $MtCO_2$/y by 2050. The abatement cost of CCS on steam methane reforming has been estimated to be 39 EUR/tCO_2.

For plastics, there are multiple abatement measures. Since the plastics value chain involves multiple stages (refining, cracking and polymerisation and incineration), CCS would have to be implemented at multiple stages to achieve near-zero emissions. Abatement costs for petrochemicals production alone have not been identified. However, abatement costs of steam cracking with CCS (in addition to waste incineration CCS), have been estimated by Material Economics to 65 EUR/tCO_2. Another option would be to use electricity for steam cracking, and waste incineration CCS, which has been estimated to have a higher abatement cost of 113 EUR/tCO_2.[34]

In general, it should be noted that the chemical industry is prioritizing CCU over CCS.[35]

Other

For ammonia production, hydrogen could be produced from electricity using water electrolysis, completely eliminating emissions on site. Ammonia production from water electrolysis in 2050 has been estimated by Material Economics to have an abatement cost between 108 and 215 EUR/tCO_2, with electricity costs of 40-60 EUR/MWh.[34] Other abatement measures include more efficient use of fertilizers, reduced food waste, and substitution with organic fertilizer.

The use of green hydrogen for ammonia production would lead to a significant increase in the demand for electricity: 125 TWh more electricity than today which is about the Norwegian annual electricity production or 4% of the EU net annual production.

For petrochemicals and especially plastics, there are a number of options for mitigation of emissions. A number of these involve reduced production of new plastics, and also have potential to reduce emissions in other industries in the value chain, including refining and waste incineration. Substitution with other materials in packaging or components has some potential. Mechanical recycling of plastics, where sorted plastic waste is shredded and reprocessed into new plastic products, could play a larger role than today in reducing emissions from the chemical sector. Mechanical recycling currently replaces around 6% of the need for primary production in the EU, reduces emissions to 0.5 tonnes CO_2 per tonne of plastic. The abatement cost of mechanical recycling is estimated to be negative but can only be applied to up to one third of end of life plastics.[34]

Chemical recycling of waste such as plastics, by breaking them down into new feedstocks could be an important abatement measure for the chemical industry. Material Economics has estimated the abatement cost of chemical recycling to be 121 EUR/tCO_2.[34]

The processes of cracking and reforming petrochemicals are energy intensive, and heat production can represent 30-70% of emissions. Electrification or hydrogen use for heat and processes is another abatement alternative, but involves relatively high abatement costs. Some residual components from these processes are used as energy inputs. Cracking results in by-products which are used as fuel in the process and would otherwise have to be utilised in other ways, while costs for electricity and/or hydrogen would increase. An estimate of the relative costs of electrification versus CCS on these processes indicated that electrification would be more costly.

[34] Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry

[35] CSLF, Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs) - From Energy/Emission Intensive Industries to Net Zero Emission Industries, draft report – July 2019

Bio resources such as methanol or forest fibre can be used as feedstock to produce a large share of chemicals, either as identical chemical products or chemicals with similar uses[36]. In one of the industry's scenarios, biomass usage could be up to 640 TWh, with the remaining 750 TWh from oil or natural gas.[37] Use of biobased feedstock has an estimated abatement cost of 139 EUR/tCO_2.[38]

2.2.3 Summary chemicals

Table 4 - Summary of chemicals/petrochemicals

Emissions 2017 (MtCO_2)	102 (175 plants)
CCS important for decarbonization:	
Ammonia/hydrogen	Medium-electrolysis is also an option
Petrochemicals	Medium-recycling and electricity is also an option
Cost of CCS (EUR/tCO_2)	
Ammonia/hydrogen	39
Petrochemicals	65-113
Cost of alternative measures (EUR/tCO_2)	
Ammonia/hydrogen	108-215 (green hydrogen)
Petrochemicals	121-139 (chemical recycling, bio)
Scenario capture 2030 (MtCO_2/y)	0-10
Scenario capture 2050 (MtCO_2/y)	30
Technical capturable[39] volume (MtCO_2/y) – all Europe	39
Role of CCS	
Ammonia/hydrogen	**High**[40]
Petrochemicals	**Medium**

[36] https://www.ies.be/files/Industrial_Value_Chain_25sept.pdf

[37] CEFIC / Ecofys, European chemistry for growth - Unlocking a competitive, low carbon and energy efficient future,2013

[38] Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry

[39] Capturable CO_2 emissions - See Box 3 - Capturable volumes

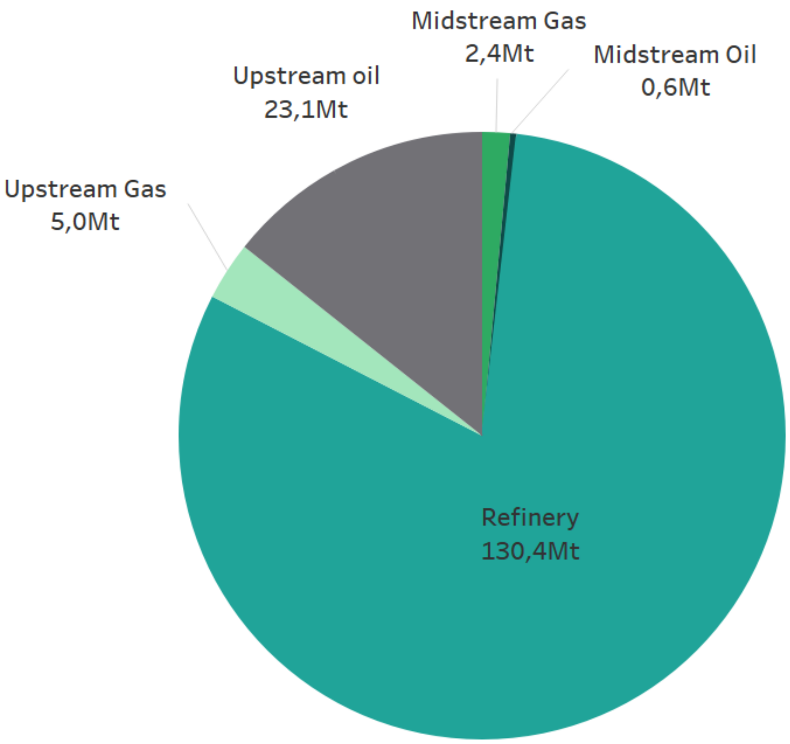
[40] See hydrogen chapter - 2.6

2.3 Refining

2.3.1 Sector emissions and plans

Refining represents most of the oil and gas segment CO_2 emissions in Europe. In 2017, 130 $MtCO_2$ were emitted from 94 refineries (E-PRTR).

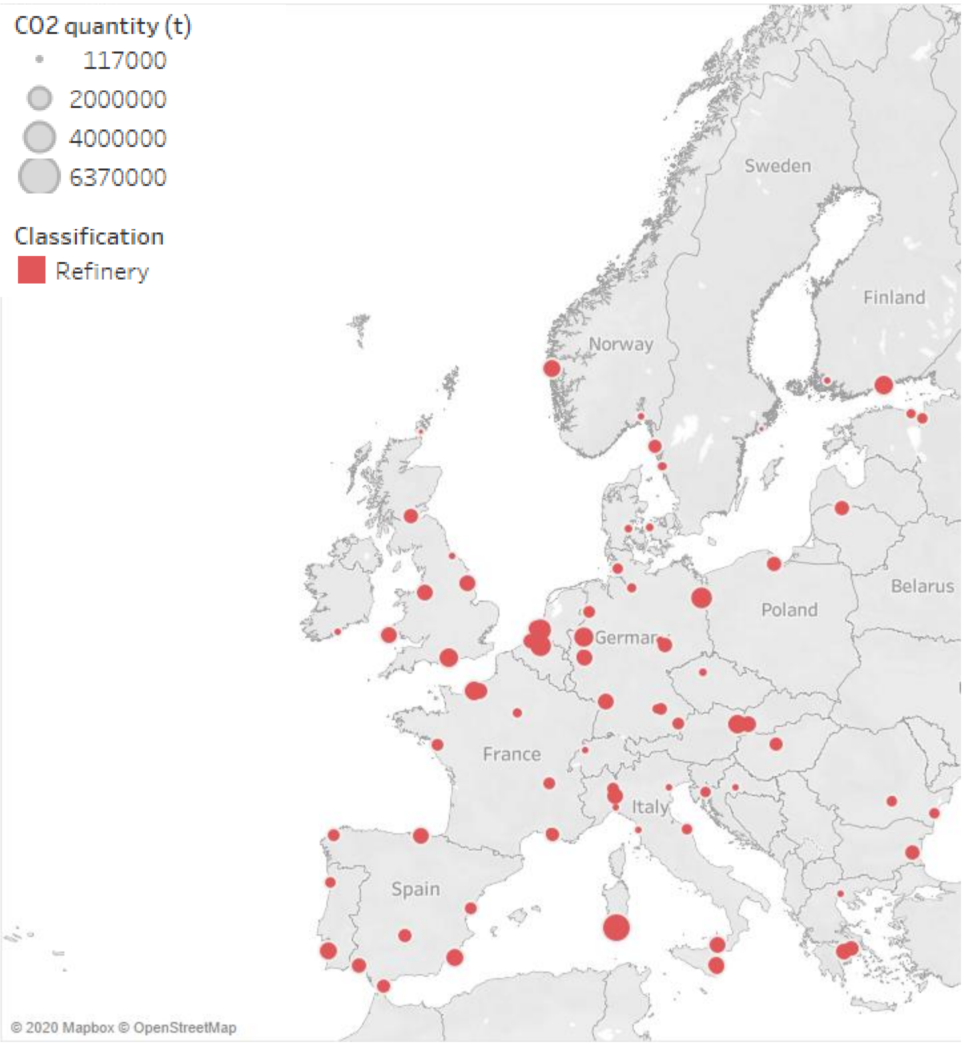
Figure 8: CO_2 emissions from the oil and gas sector in 2017 – Large stationary sources (>100 $ktCO_2$/y)



Source: Data: E-PRTR / Carbon Limits Analysis

Refineries are distributed all over Europe. Their average emissions are of 1.3 $MtCO_2$/y.

Figure 9: Location of the refineries in Europe and CO_2 emissions in 2017 for plants emitting more than 100 ktCO_2/y



Source: Data: E-PRTR / Carbon Limits Analysis

The European refining association, CONCAWE; has currently not published a net-zero roadmap. However, in 2019, the industry looked into the measures required for a decrease of 25% by 2030 and 52-62% by 2050 in the EU refining system.[41] Another study for Fuels Europe refers to a possible refinery emissions reduction of 50% without CCS and 70% with CCS by 2050.[42]

2.3.2 Available abatement measures

The abatement measures considered by CONCAWE for the refining sector are the following ones:

- Energy efficiency through refinery process efficiency improvement (continuous improvement, major capital projects, inter-unit heat integration), increased recovery of refinery low grade heat for export and electricity production

[41] CONCAWE, CO_2 reduction technologies – opportunities within the EU Refining system (2030/2050) – Scope 1 & 2, Report no. 8/19, July 2019

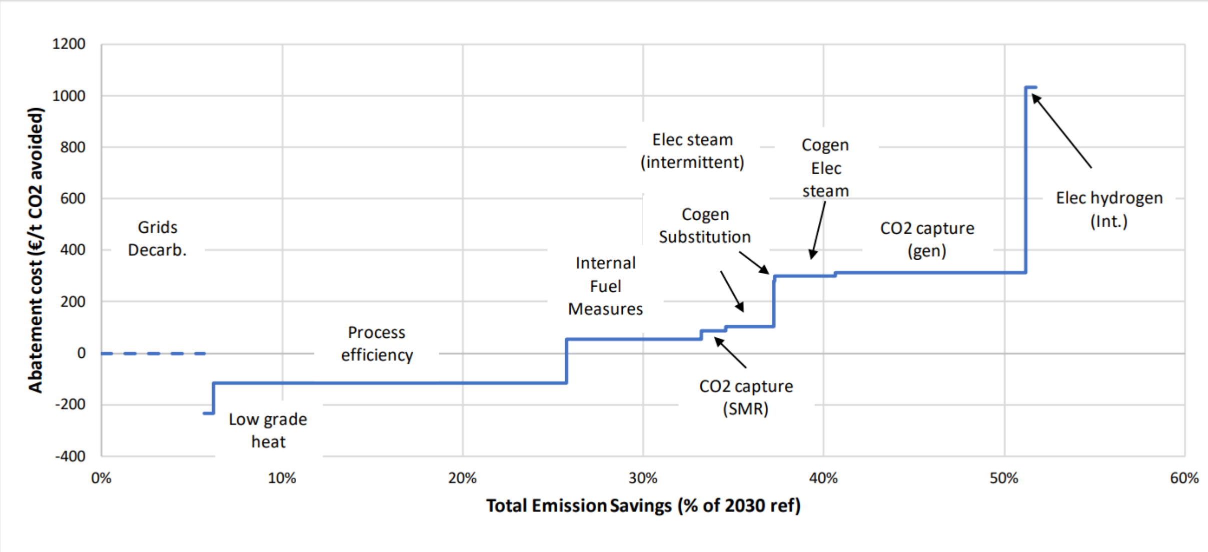
[42] https://www.fuelseurope.eu/wp-content/uploads/DEF_2018_V2050_Narratives_EN_digital.pdf

- Use of Low Carbon Energy sources through benefitting from the decarbonization of the gas and the grid, reduction of liquid fuel burning, improved recovery of H_2 and LPG from fuel gas, electrification (rotating machines), decrease of own generation – import low carbon electricity, substitution of fired boilers and heaters by electric heaters, electrolysis to produce H_2
- CCS

CCS

CONCAWE established a marginal abatement cost curve and CCS is among the middle to high abatement cost technologies (see Figure 10) with a calculated cost of 87-103 EUR/tCO_2 for Steam Methane Reforming (SMR) and 240-359 EUR/tCO_2 for other sources. Some other publications show lower abatement costs.[43]

Figure 10: Abatement cost curve for the refining sector



Source: Concawe, 2019

A refinery has multiple CO_2 emission sources, with different characteristics. There can be up to 20 or 30 stacks, with varying flowrates, concentrations, and pressures. From a technical-economic perspective, it would not be feasible to capture CO_2 from all sources. After consultation with experts in the field, it is assumed that approximately 45% can be captured at feasible costs. One of the most relevant sources is hydrogen production from steam methane reforming (SMR) where the CO_2 concentration and pressure is high. Other sources such as the fluid catalytic cracker can also be interesting for CCS, due to the high concentration in the flue gas. All refineries have a different layout, usually with emissions from a main combined heat and power unit and/or dispersed boilers/heaters, and a flare.

According to CONCAWE, very low levels of CCS are expected by 2030 but in 2050, CCS could represent 8 to 25% of emission reductions, i.e. 10 - 30 MtCO_2/y.

[43] CONCAWE is taking into account a 15% discount rate. The high costs are related to the high extra energy consumption of the CCS process as of today. Further technology development would decrease the cost. CONCAWE considered higher natural gas price than other studies and accounted in the avoided CO_2 the emissions from the gas consumption for the extra energy consumption.

2.3.3 Summary

Table 5 - Summary of refining

Emissions 2017 ($MtCO_2$)	130 (94 plants)
CCS important for decarbonisation	High
Cost of CCS (EUR/tCO_2)	
Steam methane reforming	40-103[44]
Others	240-359
Cost of other abatement options (EUR/tCO_2)	
Steam methane reforming	High (H_2 electrolysis)
Others	Low (energy efficiency), High (electrification)
Scenario capture 2030 ($MtCO_2$/y)	Very low
Scenario capture 2050 ($MtCO_2$/y)	10-30
Technical capturable volume ($MtCO_2$/y) – all Europe	59
Role of CCS	**Medium**

2.4 Waste-to-Energy

The EU waste hierarchy is the guiding principle for waste policy in the EU. The hierarchy gives preference to prevention of waste first, followed by reuse, recycling, energy recovery, and finally disposal.[45] Waste-to-energy plants incinerate waste streams and recover the heat energy for use in power and heat production.

2.4.1 Sector emissions and plans

In Europe, there is a waste-to-energy capacity of 90 Mt[46] residual waste per year divided on about 500 waste-to-energy plants. Of these, 325 have emissions over 100,000 tCO_2. About 50% of the energy from waste combusted is of fossil origin, and the other 50% is biological. For each tonne of waste incinerated, approximately one tonne of CO_2 is produced. The large waste-to-energy plants had reported emissions of 67 $MtCO_2$ in 2017[47]. Most plants are emitting from 100 to 500 $ktCO_2$/y. Waste-to-energy plants produce about 90 TWh heat and 39 TWh power per year. The largest plants are typically located near the large cities.

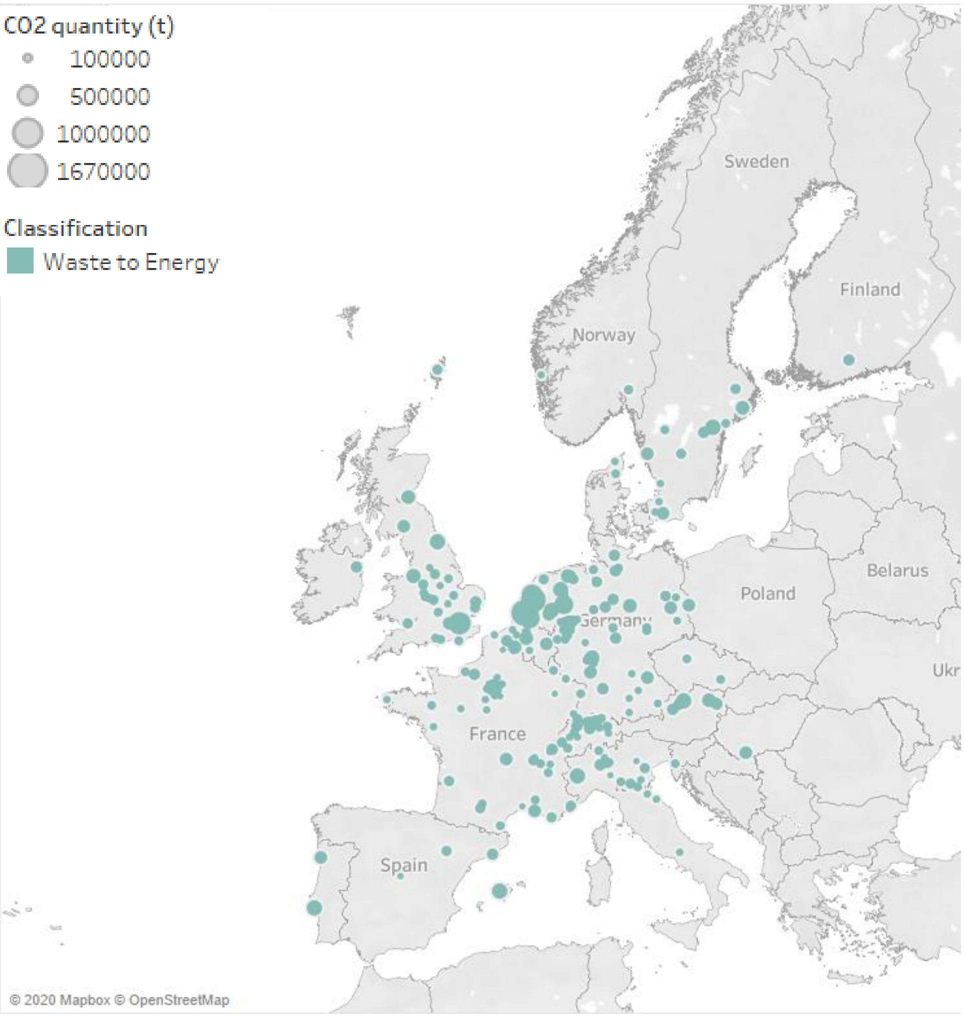
[44] CONCAWE abatement cost of hydrogen production with CCS are high compared to other references. The minimum in this range comes from other references

[45] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0098-20180705&qid=1593648305761&from=en

[46] https://www.cewep.eu/cewep-capacity-calculations/

[47] Not all countries report biogenic CO_2 emissions.

Figure 11: Location of the waste-to-energy plants in Europe and CO_2 emissions in 2017 for plants emitting more than 100 $ktCO_2/y$



Source: Data: E-PRTR / Carbon Limits Analysis

Policies which increase resource efficiency, increase recycling, or restrict single use of for example plastics, all contribute to reduction of waste streams which otherwise would likely be incinerated. On the other hand, policies which limit the use of landfills for waste contribute to more need for energy recycling of waste. The Landfill directive[48] has set a target for member states to landfill less than 10% of their waste by 2035, while 10 member states in 2018 landfilled more than 50% of their municipal waste.[49]

CEWEP, the European waste-to-energy association, assessed in 2019 what the goals in the EU recycling targets for 2035[50] would require of waste-to-energy capacities.[51] With about 246 Mt of municipal waste and 295 Mt of commercial/industrial waste in 2035, the assessment assumes that 76% and 80% of the streams, respectively are separated out for recycling or composting. From each of these, residue waste streams from sorting and pre-treatment also arise. Finally, residual non-recycled

48 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0850&from=EN

49 https://www.cewep.eu/municipal-waste-treatment-2018/

50 https://eur-lex.europa.eu/legal-content/en/TXT/PDF/?uri=CELEX:32018L0851&from=EN

51 https://www.cewep.eu/cewep-capacity-calculations/

waste streams are estimated to be 142 Mt waste. Compared to current waste-to-energy and co-incineration capacities, an increase of about 40 Mt would be required by 2035.

2.4.2 Available abatement measures

CCS

Efforts towards reducing emissions from plastics, discussed in section 2.2 above, are interlinked with waste-to-energy emissions. Measures to reduce waste streams for energy recycling, such reduced use of plastics, increased mechanical or chemical recycling of fossil waste or biogas production from biological waste are available options before the waste is generated. However, for remaining waste streams, carbon capture and storage is the only technology identified to provide deep emission reductions from waste-to-energy.[52] Since half of emissions are of biological origin, CCS can also provide negative emissions. Abatement costs for CCS on waste-to-energy facilities have been estimated by Roussanaly et al. to be around 150-200 EUR/tCO_2.[53]

2.4.3 Summary Waste-to-Energy

Table 6 - Summary of waste-to-energy

Emissions 2017 (MtCO_2)	68 (239 plants)[54]
CCS important for decarbonization	High. No abatement alternatives.
Cost (EUR/tCO_2)	150-200
Scenario capture 2030 (MtCO_2/y)	/
Scenario capture 2050 (MtCO_2/y)	/
Technical capturable[55] volume (MtCO_2/y) – all Europe	61
Role of CCS	**High**

2.5 Power generation

2.5.1 Sector emissions and plans

Power generation represented more than 22% of European emissions in 2017, corresponding to 1,007 MtCO_2e. Emissions have fallen by about 17.5% since 2012 due to expansion of renewable electricity generation capacity, primarily in the form of wind and solar energy, and a switch from coal to gas generation, see Figure 12.

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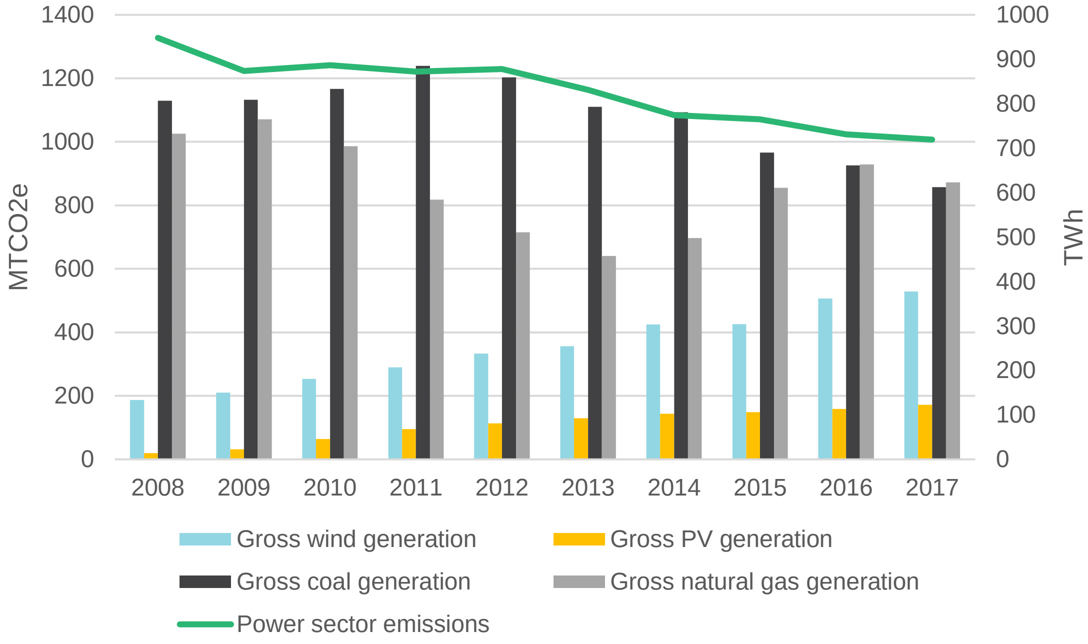
[52] Disposal through landfilling is not considered an abatement option.

[53] Roussanaly et al, Impact of Uncertainties on the Design and Cost of CCS from a Waste-to-Energy Plant, Front. Energy Res., 25 February 2020 | https://doi.org/10.3389/fenrg.2020.00017

[54] The number of facilities and emissions should increase even in ambitious recycling scenario.

[55] Capturable CO_2 emissions - See Box 3 - Capturable volumes

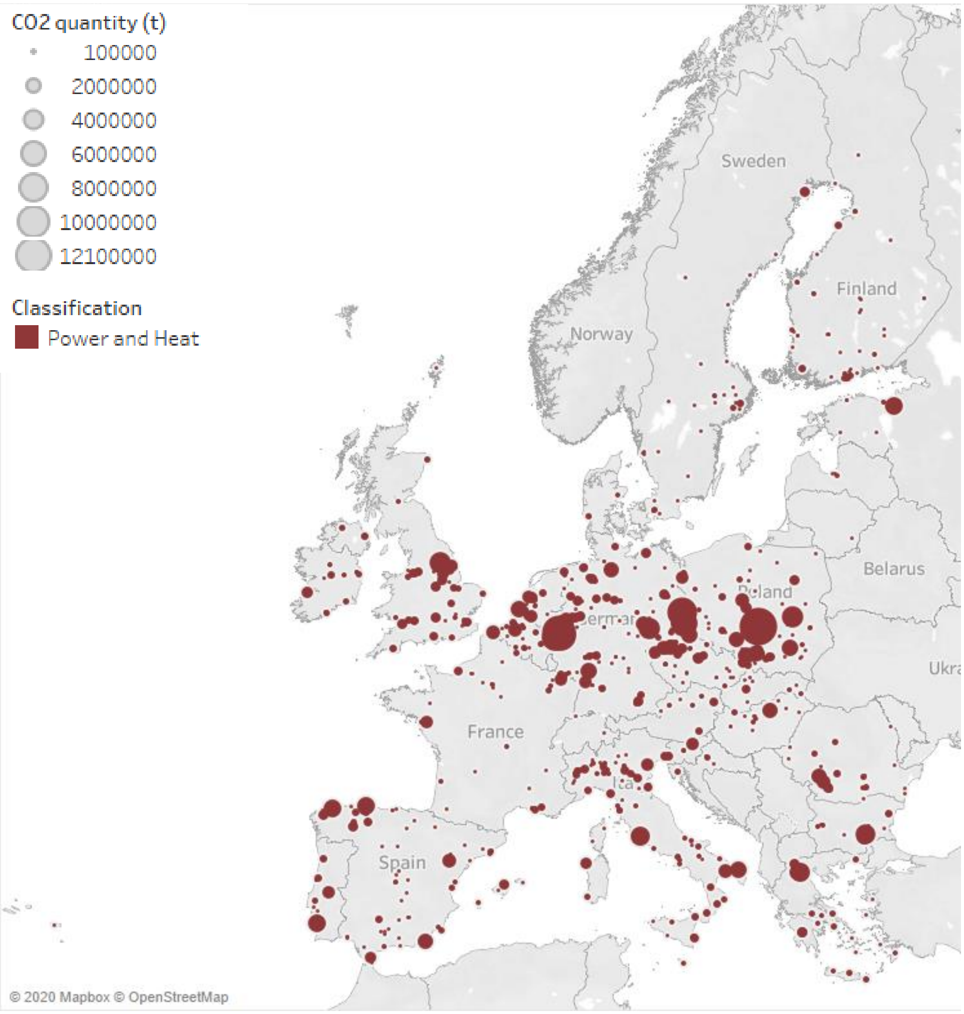
Figure 12: Power sector emissions and the development of renewables in the EU28 (2008-2017)



Source: Eurostat, 2019

As of 2017, there were 756 power and heat production plants emitting more than 100 $ktCO_2/y$, with an average emission per plant of 1.2 $MtCO_2/y$. These emissions where linked to an annual generation of 3,221 TWh of electricity. Figure 13 shows an overview of power and heat production plants in the EU with annual emission of more than 100 $ktCO_2/y$ in 2017.

Figure 13: Location of power and heat production plants in Europe and CO_2 emissions in 2017 for plants emitting more than 100 $ktCO_2/y$



Source: Data: E-PRTR / Carbon Limits Analysis

Towards 2050, demand for electricity could increase strongly, depending on the pathways chosen to decarbonise the EU. Many decarbonisation scenarios see a strong increase in electricity demand from direct electrification of sectors currently dominated by fossil fuels and/or from use of electricity to produce hydrogen.

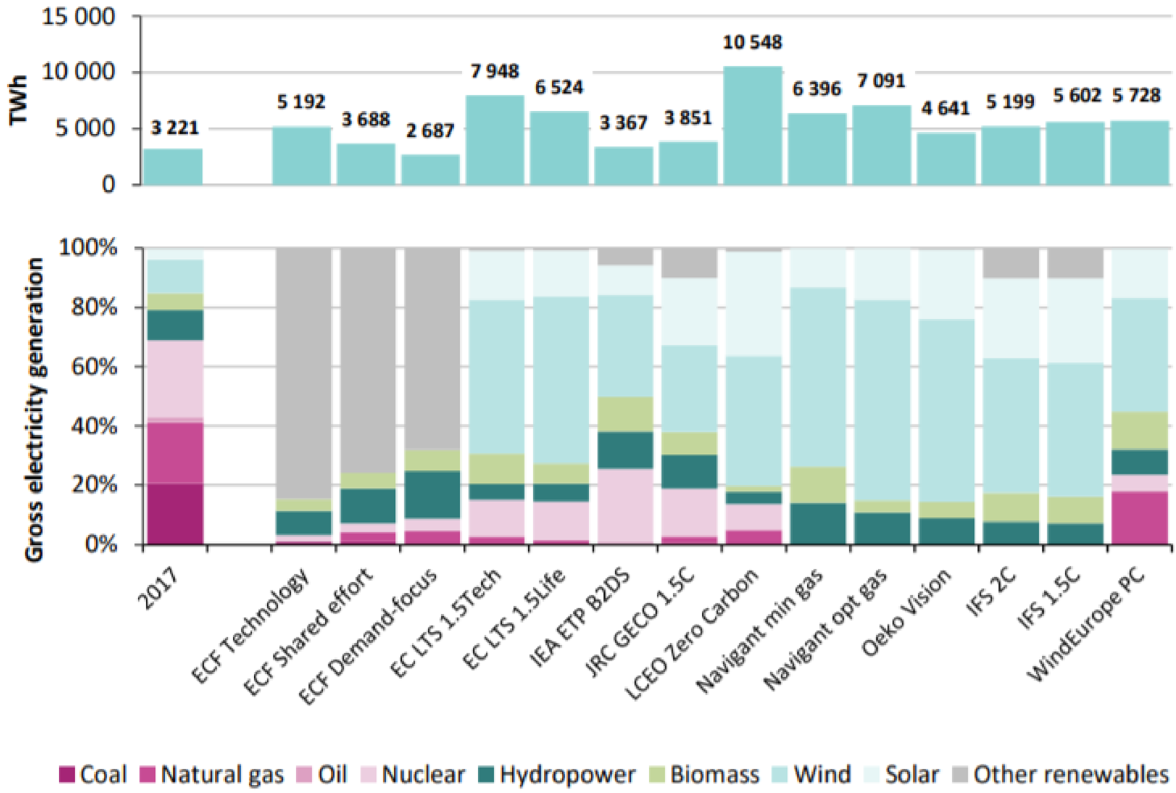
Figure 14 shows the expected electricity generation in the EU in 2050 across 14 scenarios achieving at least 90% emission reduction by 2050.[56] As can be seen, most scenarios see a significant increase from current generation volumes and only one scenario[57] sees a slight reduction. The Joint Research Centre (JRC) categorises the 14 scenarios in three groups:

- The **High growth** scenarios assume 2-4% annual growth in electricity generation, driven by demand for electricity for hydrogen production (2 600 – 3 600 TWh) and direct electrification of end user sectors. The scenarios see low to moderate levels of energy efficiency.

[56] JRC (2020) - Towards a net-zero emissions in the EU energy system by 2050 - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal
[57] European Climate Foundations Demand-side scenario, which focus on circular economy, recycling, energy efficiency and changing consumer preferences.

- The **Mid-growth** scenarios foresee 1-1.5% annual growth in electricity generation. These scenarios see increased efforts to reduce energy demand and moderate deployment of hydrogen.
- Most of the **Contraction or Slow growth** scenarios see growth of about 0.5% annually. Some of these scenarios depend on demand-side measures such as energy efficiency and life-style changes, while others assume the availability of less electricity intensive abatement options (e.g. CCS). Most see a limited deployment of hydrogen. In one scenario, electricity consumption is lower in 2050 than in 2017

Figure 14: Gross electricity generation per technology in scenarios that achieve at least 90% emission reduction by 2050



Source: JRC (2020)

2.5.2 Available abatement measures

The options for further reduction in emissions from power generation are further replacement of coal- and gas-based generation with renewable energy sources, increased nuclear power generation, application of CCS on thermal power plants and hydrogen.[58]

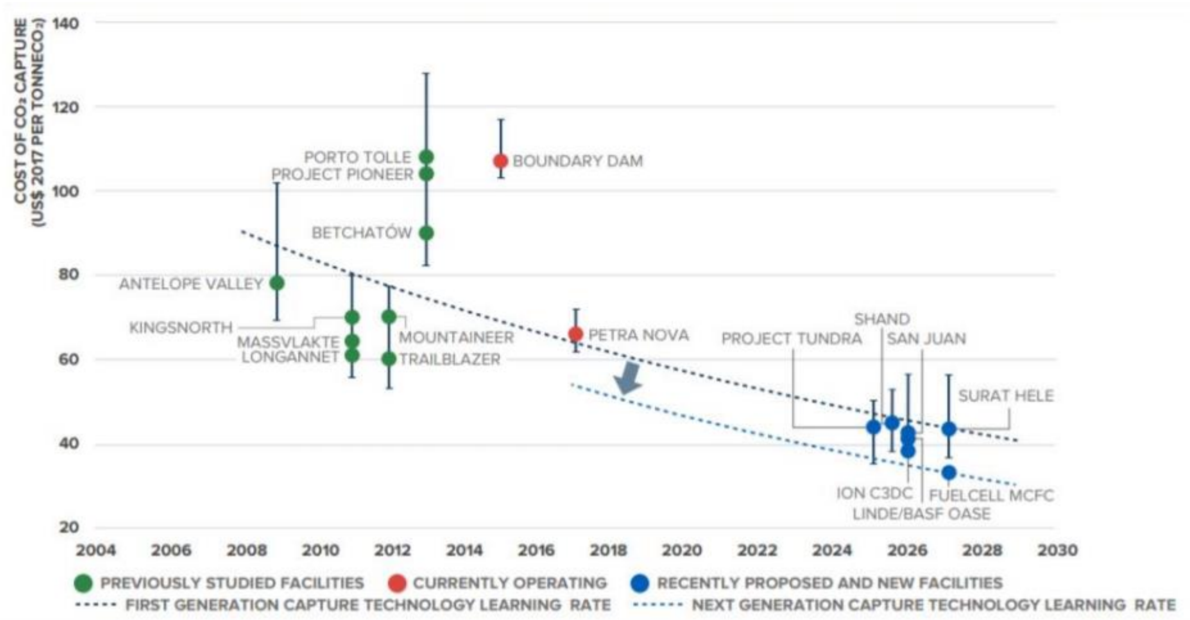
[58] In the medium-term, emission reduction can also be achieved through fuel-switching from coal to natural gas. This will however not be sufficient to cut emissions towards zero in 2050, and so is not described in more detail in the chapter.

CCS

Thermal power generation with CCS: The use of CCS on thermal power plants can reduce exhaust CO_2 emissions by over 90%[59]. The technology can be applied to thermal combustion plants using both fossil (natural gas, coal) and renewable (biomethane, biomass, biocoal) feedstock. CCS can be applied both to new thermal power generation and by retrofitting of existing plants. As flue gas from coal or gas-fired power plants contains relatively low concentrations of CO_2 (10–12 % for coal and around 3–6% for gas), the process requires a considerable amount of energy to capture the CO_2. In a recent study, SINTEF estimates that given large-scale build-out of CCS for coal-fired power plants, the total cost of capture, transport and storage would amount to an abatement cost of USD 93/tCO_2, with potential further cost reductions as the technology is developed.[60]

According to a study by the Global CCS Institute (GCCSI) the marginal abatement cost of first-generation carbon capture (excluding transport and storage) on coal power plants have gone done from around 90 USD/tCO_2 in 2008 to around 60 USD/tCO_2 today and are estimated to fall towards 40 USD/tCO_2 by 2030. The cost of next generation plant (still in the pilot phase) are expected to be about 10 USD/tCO_2 lower, thus falling to about 30 USD/tCO_2 towards 2030s.[61]

Figure 15: Levelized cost of CO_2 capture for large scale post-combustion coal CCS facilities



Source: Global CCS Institute (2019).

Another GCCSI study from 2017 that compares the cost of CCS on different applications, reports the cost of CCS per tonne of CO_2 avoided to around 78 USD/tonne for coal-fired power generation and 89 USD/t for gas-fired power generation[62], however with large regional variations. The figures apply to

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[59] Further emission reduction is technically feasible, but costs per captured tCO_2 increase as the concentration of CO_2 falls, leading to sharply increasing abatement costs for the last percentage points of CO_2.

[60] SINTEF (2019) - [Carbon Capture and Storage]

[61] GCCSI (2019): Global Status of CCS 2019 – Targeting climate change, https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

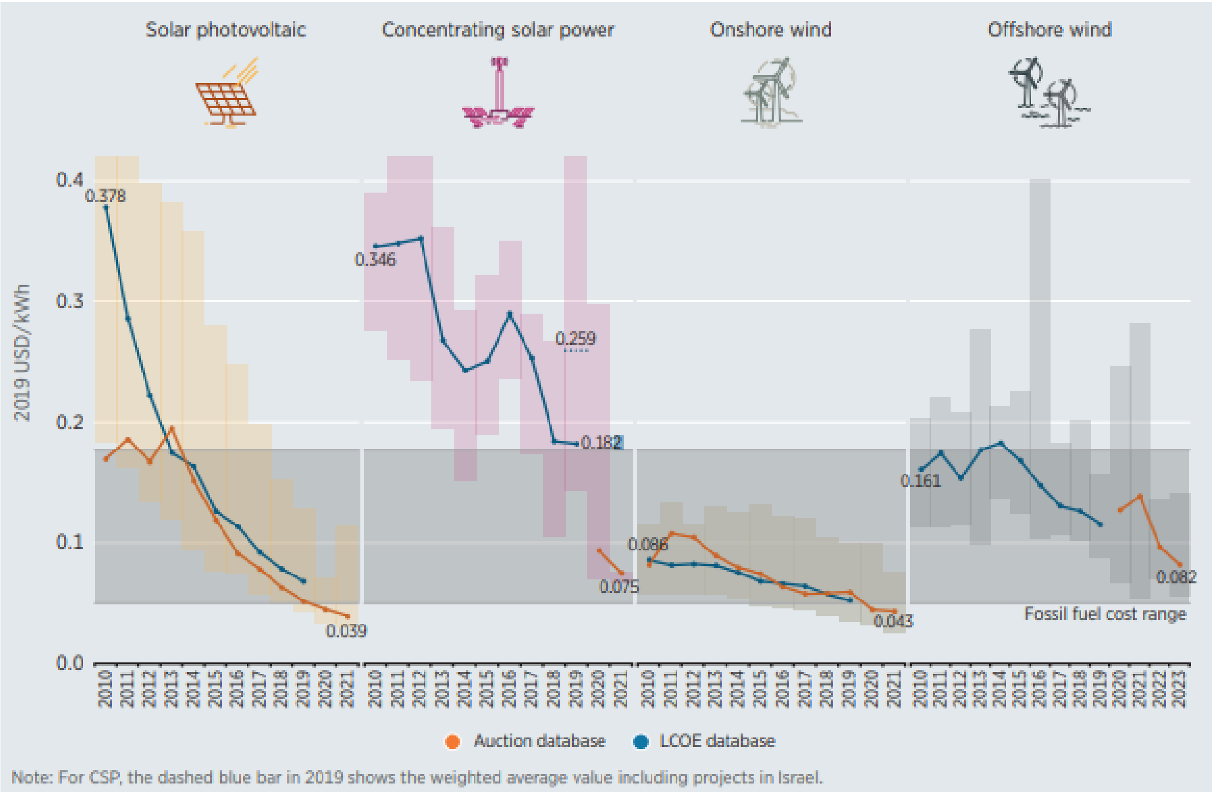
[62] Equivalent to approximately EUR 70/tCO_2 and EUR 79/tCO_2 respectively.

first-of-a-kind projects, and GCCSI foresee considerable potential for further cost reductions with increased deployment of the technology.[63]

Other

Renewable energy generation: The cost of renewable energy technologies has plummeted over the last decade (see Figure 16). In terms of full costs per kWh (Levelized Cost of Energy, LCOE), half of all renewable capacity additions in 2019 deliver electricity at a lower cost than the cheapest fossil fuel new build.[64] Further cost reductions are expected in the years to come.[65]

Figure 16: Global weighted average LCOE from utility-scale RES generation, 2010-2019 and auction results until 2021



Source: IRENA (2020)

Nuclear power generation: Nuclear power constituted about 25% of European electricity generation in 2018.[66] According to Bloomberg New Energy Finance (BNEF), European nuclear power generation costs lie in the range of 200–240 USD/MWh, far above the cost of renewable electricity.[67] Some recent studies suggest that the cost of nuclear energy generation has increased over the last 10 years, mainly due to stricter safety regulations and new reactor designs.[68] Furthermore, recent nuclear projects in

[63] GCCSI (2017): Global costs of carbon capture and storage – 2017 update, https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf

[64] IRENA (2020). Power Generation Costs 2019.
[65] NREL (2019) - Annual Technology Baseline
[66] Eurostat (2019). Electricity generation statistics.
[67] Estimated at 58-76 USD/MWh for onshore wind and 86-104 USD/MWh for solar PV according to BNEF (2019) – New Energy Outlook 2019
[68] Silvana Gamboa Palacios and Jaap Jansen, "Nuclear Energy Economics : An Update to Fact Finding Nuclear Energy," 2018, 1–13.

Europe have encountered significant public resistance and faced long delays and cost overruns.[69] However, the ability of nuclear power to provide baseload generation could be an argument for deployment despite cost issues.

Hydrogen: Hydrogen can be used to generate electricity either through combustion or through a fuel cell. Hydrogen-fired power plants can serve both as baseload and as a flexibility provider both for short-term balancing markets and for seasonal variation. There are no direct GHG emission from the consumption of hydrogen for electricity generation, but the climate footprint of hydrogen power production depends on the emission associated with the production of hydrogen (see also chapter 2.6). It is hard to determine the long-term abatement cost of using hydrogen for electricity generation, as it depends heavily on the cost of producing hydrogen. Existing natural gas fired power stations can be converted to hydrogen power stations by changing the turbine burners. [70]

Considering the cost pr. kWh, renewable energy generation is the cheapest decarbonisation option for the power sector. However, there are several reasons why abatement options in the power sector cannot simply be compared on an LCOE basis. Even in a power system dominated by renewable generation, there would also be room for, or indeed a need for complementary abatement measures.

1. *Limited renewable energy sources*: Depending on the volumes of electricity demanded in 2050, the availability of areas for competitive wind and solar power could potentially become an issue. The issue pertains both to the conditions for wind and solar generation, but also to the availability of land not in conflict with other uses.

2. *Cannibalization*: The key technologies for renewable electricity production are intermittent in nature and its intermittency does not follow demand variations. Unlike flexible generation units, such as hydropower and gas power, wind and solar generation cannot be optimized to exploit peak price periods. On the contrary, as wind generation in an area is typically highly correlated, prices tend to fall when wind generation is high, hence the term cannibalization. The cannibalization factor is higher for solar generation than for wind power.

3. *Reliability and flexibility:* To ensure stable and secure supply of energy in a system dominated by intermittent generation, the energy system is dependent on storage and flexibility services. Flexibility will be needed on all timescales, from real-time balancing to storage and/or back-up capacity that can make up for low renewable production for several weeks.

Clearly, the main abatement option in the power sector is to replace fossil fuel generation with renewable power generation. Due to the considerable reduction in the LCOE of renewable generation and its rapid expansion in the last decade, combined with ambitious climate policies, several countries have adopted coal phase-out plans and gas power generation is largely seen as a transition fuel. Nevertheless, there might be some room for CCS in the power sector related to the system needs and the demand for negative emissions.[71] In addition, for some European countries, currently heavily relying on coal power generation, CCS on coal power plants could be an attractive option.

Power plants with CCS could provide flexibility at most timescales but will compete with other flexibility options such as hydrogen, batteries and demand-side flexibility. As baseload/long-term energy backup

[69] David Keohane, "EDF Adds Further €1.5bn to Flamanville Nuclear Plant Costs," *Financial Times*, October 9, 2019, https://www.ft.com/content/fc6a8610-ea5e-11e9-a240-3b065ef5fc55.
[70] Vattenfall (2017) – Vattenfall aims for carbon-free gas power

[71] JRC (2020) – Towards a net-zero emissions in the EU energy system by 2050 - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal and EC(2018) - COM (2018) 773

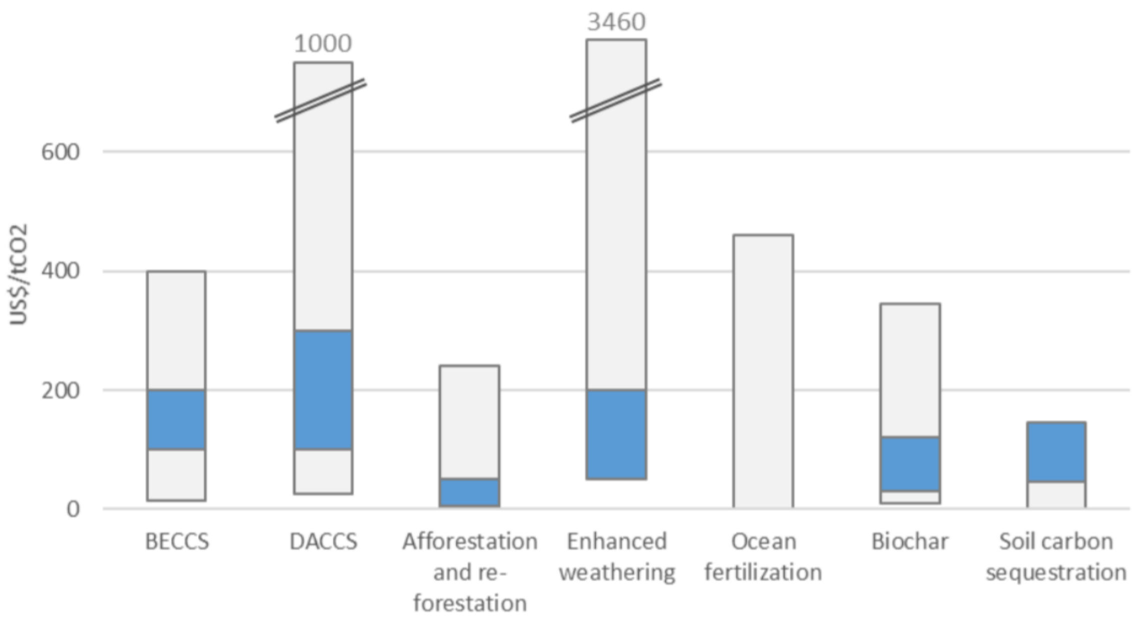
capacity, CCS mainly competes with nuclear power, and generation based on biomass and hydrogen. The main contenders for shorter-term flexibility are batteries and demand-side flexibility.

With some industry and agricultural emissions hard to abate, there will be a need for *negative emissions* in the zero-carbon economy. The combination of bioenergy for power generation combined with CCS is mentioned as one of the key technologies for providing negative emissions globally.[72] The flexibility and energy-backup that such plant could provide, represent a potential for value creation in addition to the value of electricity and carbon.

For both flexibility and negative emissions, CCS in the power sector will compete with other options. Inter alia, the role of CCS power plants to deliver flexibility will depend on the development of hydrogen as a flexibility provider as well as demand-side response developments.

For negative emissions, there are several other technologies that can deliver them including direct air capture and CCS (DACCS) and LULUCF-related measures such as afforestation. As seen in Figure 17, there is considerable uncertainty regarding the cost of the different measures for negative emissions. The three measures also vary strongly when it comes to energy- and area-intensity.

Figure 17: Cost of carbon dioxide removal technologies.



Note: The full range of costs reported in the literature, the blue colour reflect the part of the ranges the authors of the study consider as the most likely.

Source: EC (2018) – Long-term Strategy

While BECCS in the power sector produces energy, DACCS requires at least 0.14 kWh/kgCO_2 (0.5 MJ/kgCO_2). Negative emissions on the scale of 300 MtCO_2 annually by DACCS would thus require a minimum power consumption of around 42 TWh.[73]

[72] See e.g. IPCC's report on Global warming of 1.5 degrees and IEA's Sustainable Development Scenario

[73] EC (2018) – In depth analysis accompanying the A Clean Planet for All p. 189

DACCS requires far less area than BECCS (4-15 kha and 3-6 Mha per 100 $MtCO_2$ respectively), as the latter depend on the use of biological resources. Accounting for the area needed to supply the energy consumed by DACCS could reduce the difference somewhat. While seemingly the cheapest option for negative emission of the three, afforestation is also the most area-intensive, requiring 14-33 Mha per 100 $MtCO_2$.[74] Using these figures and assuming a need for 300 $MtCO_2$ of negative emissions annually in 2050, DACCS, BECCS and afforestation would require 120-450 km^2, 90 000 – 180 000 km^2 and 420 000 – 990 000 km^2 respectively. For comparison, the area of France is about 650 000 km^2.[75]

The fact that CCS in the power sector competes with numerous other technologies across several markets (energy, flexibility, negative emissions), makes it hard to determine how much of the technology will be needed to decarbonise the power sector. JRC has compared 14 studies illustrating deep decarbonisation in the EU towards 2050.[76] It finds that:

- There is a vast discrepancy between scenarios when it comes to electricity demand in 2050
- In five scenarios, no fossil power generation capacity is present in 2050
- In the scenarios where fossil fuel plants are present with or without CCS, this is explained by the need to provide the power system with flexibility or baseload.
- With the exception of one scenario (WindEurope PC[77]), which see gas fired power plants retaining about 20% market share, the role of fossil fuels is marginal in the European electricity system by 2050 (see Figure 18).
- Only four studies set explicit numbers for BECCS, ranging from 2.5 GW to 50 GW in 2050.
- Renewable energy represents between 75% and 100% of electricity generation

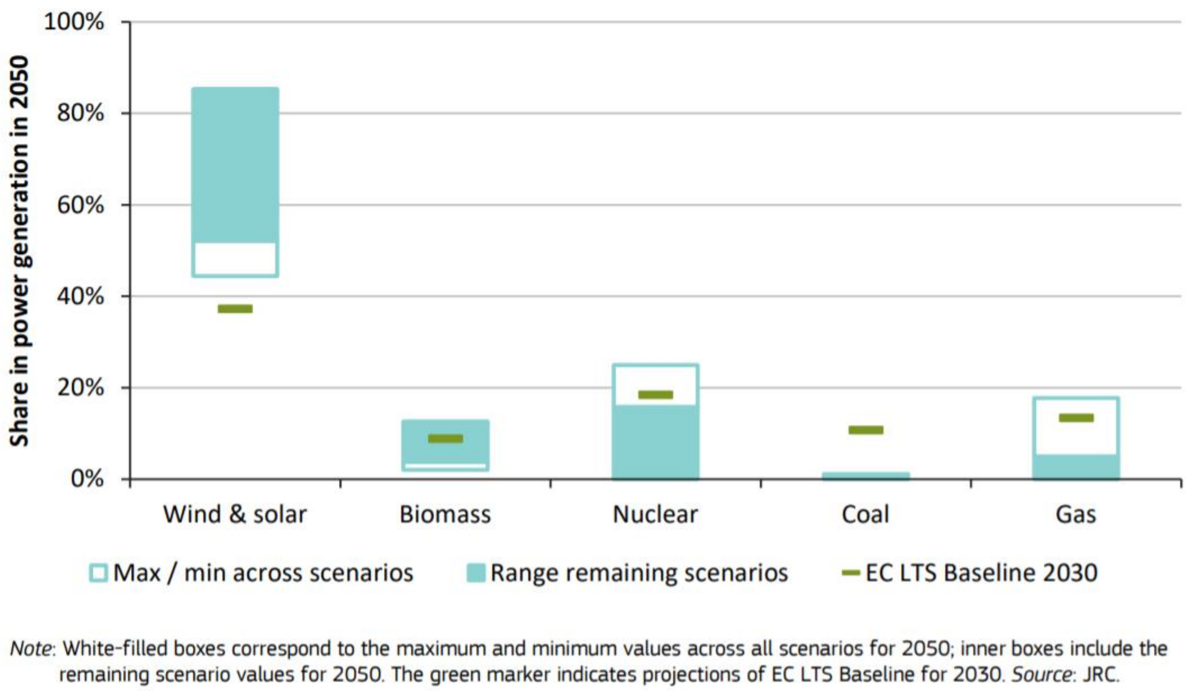
[74] EC (2018) – In depth analysis accompanying the A Clean Planet for All p. 189

[75] A broader review of various measures for negative emission is provided by Sabine Fuss et al (2018) - Negative emissions—Part 2: Costs, potentials and side effects. Retrieved from https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf

[76] JRC (2020) – Towards a net-zero emissions in the EU energy system by 2050 - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal

[77] The WindEurope Paris-Compatible scenario does not provide details on CCS volumes and only achieves a 90% emission reduction compared to 1990 levels. Full report from WindEurope (2018) available at https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-breaking-new-ground.pdf

Figure 18: Share of electricity generation per technology in scenarios that achieve at least 90% emission reduction by 2050 and benchmark with projections for 2030 under the existing policy framework



Source: JRC (2020)

Some conclusions can be drawn:

1. CCS on fossil fuel plants is unlikely to play a key role in decarbonising the European power sector as the cost per kWh of renewable alternatives are far lower.
2. It is technically feasible to decarbonise the power system without the use of CCS, but that would require other flexibility providers (e.g. hydrogen)
3. BECCS can deliver negative emissions, which is a necessity for achieving net-zero emissions in 2050.

Given that there are alternative measures to decarbonise the power sector and provide necessary baseload and flexibility, the lower end of the range could be close to 0 tCO_2/y in 2050. At the other end of the range, provided large amounts of negative emission is needed, the 1.5 TECH scenario from the EU long-term strategy can be used as an upper limit. Here, annual CCS volumes of 218 $MtCO_2$ is envisioned from the power sector, of which 178 associated with bioenergy.[78]

[78] EC(2018) - A Clean Planet for All - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy COM (2018) 773

2.5.3 Summary Power generation

Table 7 - Summary power generation

Power - Assessment of interest for CCS - Potential	
Emissions 2017 ($MtCO_2$)	1,007 $MtCO_2$
CCS important for decarbonisation	No
Cost of CCS (EUR/tCO_2)	70-105 EUR/tCO_2
Scenario capture 2030 ($MtCO_2/y$)	/
Scenario capture 2050 ($MtCO_2/y$)	0-218
Technical capturable[79] volume ($MtCO_2/y$) – all Europe *Not accounting for coal phase out nor BECCS*	841
Role of CCS	**Low** Interest for BECCS

2.6 Hydrogen

2.6.1 Sector emissions

Currently, hydrogen is used primarily as a feedstock in industrial processes. A total of 8 Mt of hydrogen is consumed annually in the EU of which 90% for industrial purposes.[80] There are no emissions associated with the consumption of hydrogen. However, the most widespread processes for producing hydrogen today, steam methane reforming (SMR) of natural gas, emits approximately 8-12 tCO_2 per tonne of hydrogen.[81] Using these estimates, the annual emissions associated with production of the hydrogen consumed in the EU today is 64–96 $MtCO_2$. The use of CCS to abate existing emission from hydrogen used for industrial purposes are accounted for in the previously described sectors (chemicals / petrochemicals and refineries).

In addition to being used as feedstock in industrial processes, using hydrogen as an energy carrier is seen as a potential future enabler of emission reduction across multiple sectors. Hydrogen can be used for energy purposes either directly through combustion or in fuel cells, or in combination with electricity and CO_2 to produce synthetic fuels and gases. In various forms, hydrogen can be an abatement option across all sectors. Several analysts point out hydrogen's potential in the transport and industrial sectors, while some also see it as an important abatement option for households and in the power sector.[82] In this section, we discuss the potential role of CCS in the production of hydrogen for these new areas of application.

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[79] Capturable CO_2 emissions - See Box 3 - Capturable volumes

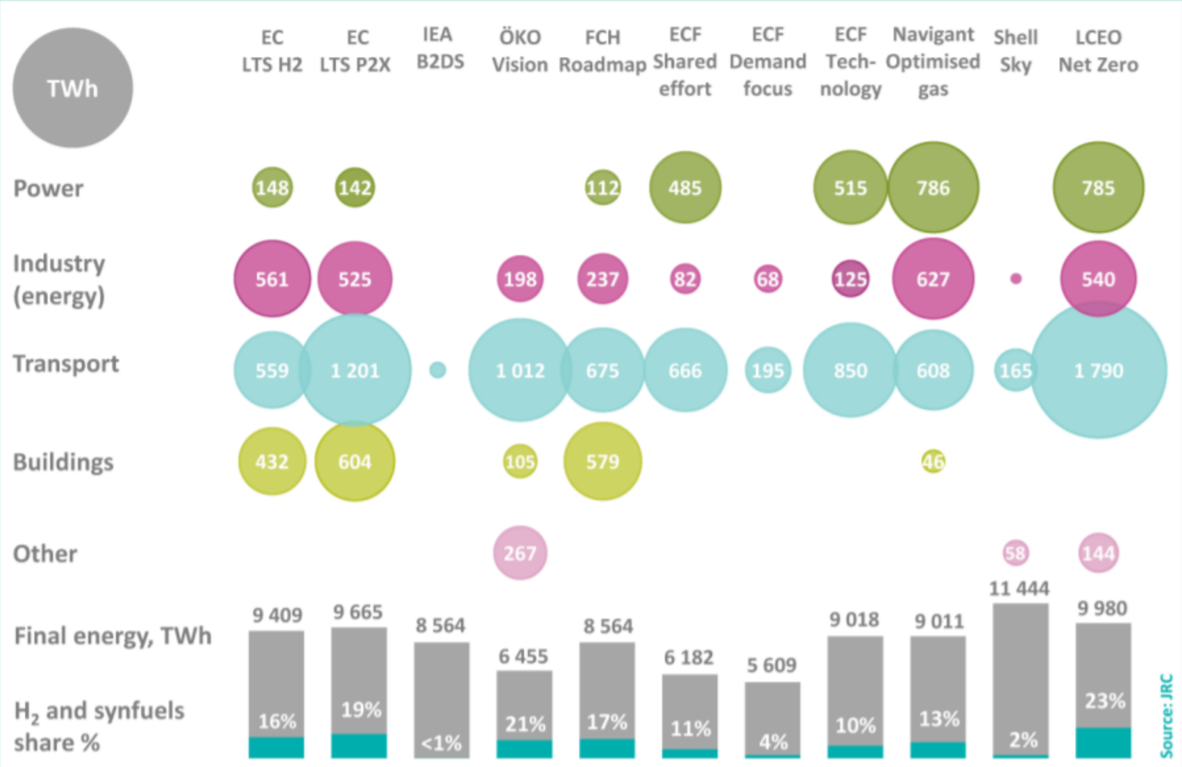
[80] CertifyEU (2015) - Overview of the market segmentation for hydrogen across potential customer groups, based on key application areas

[81] Rocky Mountain Institute (2020) - Hydrogen's Decarbonization Impact for Industry Near-term challenges and long-term potential

[82] JRC (2020) – Hydrogen use in EU decarbonisation scenarios.

Scenarios for the role of hydrogen vary significantly and depend on the cost of hydrogen relative to other abatement options. Important assumptions regarding e.g. technological development and availability of e.g. renewable energy sources are made under considerable uncertainty. A range of results is presented in Figure 19.

Figure 19: Consumption of hydrogen and share in final energy in EU decarbonisation scenarios in 2050. TWh



Source: JRC (2020)

2.6.2 Available abatement measures

Hydrogen can be produced from different feedstocks and processes. Most of the current hydrogen consumption in industry is supplied by steam reformation (SMR) of natural gas, with most of the remaining being by-products from other industrial processes. A minor share is produced by electrolysis.

The literature points to three key options to cut emissions from current and new hydrogen production: Reformation of natural gas with CCS, gasification of coal with CCS, and production of hydrogen with electrolysis using renewable electricity.[83]

[83] Hydrogen Council (2020) - Path to hydrogen competitiveness A cost perspective

CCS

Reformation of natural gas with CCS: Hydrogen is produced by steam methane reforming (SMR) or auto-thermal reforming (ATR) of natural gas. In literature the upper limit for the capture rate is often assumed at 85-90% for SMR and above 90% for ATR.[84] The industrial partners behind the H21 North of England project, plans for a 94% capture rate using an ATR process[85]. A study by CE Delft (2018) notes that while SMR is a widely applied technology, "[…] ATR seems to bear the most potential for a blue hydrogen chain since it enables higher CO_2 capture percentage."[84]

Coal gasification with CCS: Hydrogen can also be produced through a reaction between coal, oxygen and steam combined with CCS[83]. Coal gasification generates about four times as much CO_2 for storage than reformation of natural gas and have higher residual emissions pr. kg of H_2. These disadvantages would need to be weighed up for by a cost advantage of coal over natural gas.[83]

Non-CCS options

Electrolysis: Hydrogen can be produced by splitting water molecules into hydrogen and oxygen using electricity in a process called electrolysis. To produce 1 kg of hydrogen, approximately 50 kWh of electricity is required[86]. The two main technologies for hydrogen production by electrolysis are:

- *Alkaline*: Using a saline solution to separate hydrogen from water using electricity. The technology is mature and applied for most hydrogen production from electrolysis today.
- *Proton-exchange membrane (PEM)*: Employs a solid membrane to separate hydrogen and water using electricity. The technology is less mature than alkaline.[87]

The extent to which hydrogen produced from electrolysis provide emission reduction compared to hydrogen based on fossil fuels depends on the origin of the electricity that is used to produce it.

Cost of abatement options

Hydrogen Council underlines that the availability of low-cost energy resources (renewable electricity, gas and coal) is a key determining factor for the relative competitiveness of the different low-emission hydrogen production processes.

They estimate that in Europe, the cost of hydrogen from natural gas with CCS would be around 2.10 USD/kgH_2 in 2020, falling to 1.70 USD/kgH_2 in 2030 due to reduced cost of CCS.[88] In regions with ample supply of low-cost renewable power generation, the cost of hydrogen production could fall from 2.50 USD/kgH_2 today to 1.20 USD/kgH_2 in 2030. Hydrogen from offshore wind in Europe is estimated to cost about 6 USD/kg today, falling to 2.50 USD/kgH_2 in 2030 due to expected cost reductions for both electrolysers and offshore wind generation. These numbers suggest that hydrogen from natural gas with CCS would still be cheaper than hydrogen produced by electrolysis from offshore wind in 2030.

In addition to the cost of electricity, the cost and load factor[89] of the electrolysers are important elements in the hydrogen cost. Figure 20 shows how the cost pr. kg of hydrogen from renewable

[84] CE Delft (2018) – Feasibility study into blue hydrogen – Technical, economic & sustainability analysis.
[85] H21 (2018) – H21 NoE Report/2018
[86] Rocky Mountain Institute (2020) - Hydrogen's Decarbonization Impact for Industry Near-term challenges and long-term potential
[87] Hydrogen Council (2020) - Path to hydrogen competitiveness A cost perspective

[88] It is unclear what is assumed with regards to the cost of remaining emissions (non-captured CO_2) in the calculations.
[89] Actual annual production as a share of theoretical maximum annual production. A low load factor means that the fixed cost of the electrolysers will be spread on less hydrogen, leading to a higher unit cost.

energy and electrolysis vary with the cost of renewable energy generation (LCOE[90] of 0-100 USD/MWh), load factor (10–50%) and electrolyser investment cost (750 USD/kW –250 USD/kW). From the figure, we can see the importance of availability of low-cost renewable electricity sources. Assuming an electrolyser cost of 250 USD/kW and a load factor for 40%, hydrogen produced from renewable energy sources at a cost of 20 USD/MWh result in a cost of 1.6 USD/kgH_2. This cost is lower than that assumed for hydrogen from natural gas with CCS in Europe in 2030 (1.7 USD/kg). However, if the hydrogen is produced from renewable electricity costing 30 USD/MWh, it is already more expensive (2.1 USD/kg) than the natural gas solution. The competitiveness of hydrogen based on renewable electricity is therefore highly dependent on the availability of low-cost renewable electricity generation.

Figure 20: Cost of renewable hydrogen with varying LCOE and load factors. USD/kgH_2.

< USD 2/kg | USD 2-3/kg | USD 3-4/kg | > USD 4/kg | Viable medium-term (<2030)

LCOE / Capex electrolyser	USD 750/kW					USD 500/kW					USD 250/kW				
Load factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2.0
USD 40/MWh	7.5	4.7	3.8	3.3	3.0	6.1	4.0	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
USD 50/MWh	8.0	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.7	3.2	3.0	2.9
USD 100/MWh	10.3	7.5	6.5	6.1	5.8	8.9	6.7	6.0	5.7	5.5	7.4	6.0	5.6	5.3	5.2

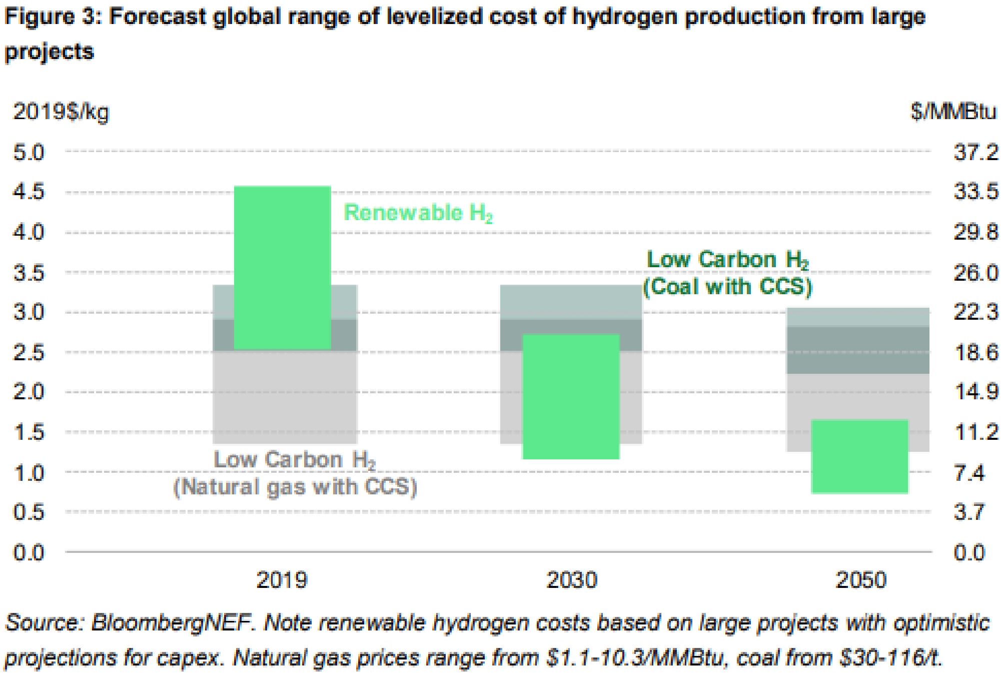
Source: Hydrogen Council/McKinsey (2020)[91]

Bloomberg New Energy Finance (BNEF) paints a similar picture for the relative cost of hydrogen from natural gas with CCS and hydrogen from electrolysis based on renewable electricity. As can be seen in Figure 21, hydrogen from natural gas with CCS is the cheaper option today. In 2030, the cost of hydrogen from electrolysis and hydrogen from natural gas with CCS overlaps. In the long term, hydrogen from electrolysis sees much stronger cost reduction than hydrogen from natural gas with CCS. By 2050, BNEF estimates that green hydrogen could be produced at 0.7–1.6 USD/kgH_2.

[90] LCOE is an abbreviation of Levelized Cost of Energy, which is a figure that is meant to reflect the average cost pr. energy unit produced over the generation facility's lifetime taking into account both capital expenditures and operational expenditures.

[91] Hydrogen Council (2020) - [Path to hydrogen competitiveness A cost perspective]

Figure 21: Global cost ranges of producing green and blue hydrogen in 2019, 2030 and 2050



Source: BNEF[92]

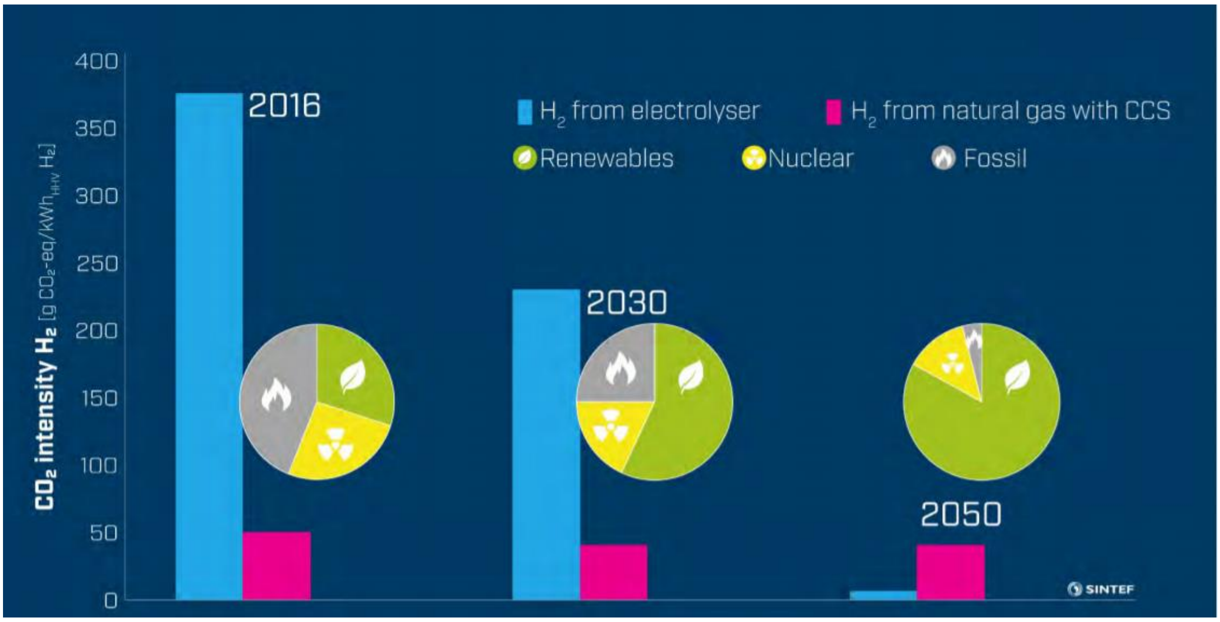
In addition to appearing cost competitive in the short- and medium term, hydrogen from natural gas with CCS would also be less emission-intensive than hydrogen from electrolysis assuming that the electricity consumed has a carbon content equal to the average carbon content of one kWh produced in the EU.

SINTEF (2019) has compared the associated emissions from hydrogen production from electrolysis and natural gas with CCS. The comparison is done assuming the average emission intensity of the EU electricity generation in the EU as it was in 2016 and as it is estimated in scenarios from IRENA in 2030 and the EU Commission in 2050. They conclude that the emission-intensity of hydrogen from electrolysis is higher than that of natural gas with CCS for several decades to come. The results are illustrated in Figure 22 below.[93]

[92] BNEF (2020). Hydrogen Economy Outlook

[93] SINTEF (2019) – Status of hydrogen production with CO2 capture – including perspectives on emissions and scale. Retrieved from https://www.cslforum.org/cslf/sites/default/files/documents/Chatou2019/Storset_Status-of-H2-Production-with-CO2-Capture.pdf

Figure 22: CO_2 emission intensity of hydrogen production by electrolysis and SMR of natural gas with CCS.



Source: SINTEF (2019)

The perceived emission-intensity of hydrogen from electrolysis will vary strongly with the assumptions regarding the origin of the electricity used to produce the hydrogen. Some initiatives aim to develop ways of documenting the use of renewable electricity for hydrogen production. One example is the EU initiative called CertifHy, which aims to establish a certification scheme for green and low-emission hydrogen based on a Guarantees-of-Origin system.[94][95] While such certification schemes might provide an extra source of revenue for renewable electricity producers, it will also lead to an increased cost of production of hydrogen from electrolysis. Furthermore, cheap renewable electricity resources are a scarce resource, meaning that as demand increase, more expensive projects must be realised to satisfy it. The increased demand of renewable electricity for hydrogen production might therefore lead to a slower transition to renewable electricity in other parts of the economy, thus leading to higher emissions elsewhere.

As a consequence, the assumption regarding availability of sufficient volumes of competitively priced renewable electricity is a key factor in determining the competitiveness of hydrogen from electrolysis versus hydrogen from natural gas with CCS. In turn, the volumes and trajectory of hydrogen demanded for decarbonisation of the European economy becomes an important factor.

As discussed in chapter 2.5.1, the electricity generation levels assumed for the EU in 2050 are higher in scenarios assuming a major role for hydrogen in decarbonising the economy, with 2,600 – 3,600 TWh of renewable electricity used for hydrogen production. For comparison, all renewable electricity in Germany in 2018 represented 219 TWh.[96] A similar amount of hydrogen produced from natural gas

[94] CertifHy (2020) - https://www.certifhy.eu/project-description/why-a-guarantee-of-origin-for-green-hydrogen.html

[95] CertifHy (2019) - CertifHy-SD Hydrogen Criteria. Retrieved from https://www.certifhy.eu/images/media/files/CertifHy_2_deliverables/CertifHy_H2-criteria-definition_V1-1_2019-03-13_clean_endorsed.pdf

[96] Fraunhofer (2019) - Renewable Sources Contribute More Than 40 Percent to Germany's Public Net Electricity Generation in 2018

with CCS would require approximately 260-360 bcm of natural gas[97], which is about 2-3 times the Norwegian gas exports in 2017.[98]

In addition, renewable electricity is also needed for the decarbonisation of existing fossil production and any increase in electricity demand driven by e.g. electrification of new sectors. In the two net-zero scenarios developed in the EU's Long-term Strategy, total electricity generation increase by 103 – 147% in 2050 compared to 2017.[99] The increase is mainly achieved through an assumed expansion of solar, onshore and offshore wind power, but the analysis does not contain a detailed analysis of the areas necessary to develop these resources.

While the above refers to costs of production, the cost of infrastructure for transport, distribution and storage of hydrogen from the production site to final consumption is also an important factor. According to McKinsey/Hydrogen Council transport and distribution can make up half of the final cost of hydrogen for decentralised consumption of hydrogen.[100] The three main options for hydrogen transport are trucks with compressed hydrogen, trucks with liquid hydrogen and pipeline transport. The distance and volume of hydrogen determines which option is most cost-efficient. Hydrogen produced from electrolysis is less dependent on scale and can therefore in some cases draw advantage from being located close to consumption, thus leading to less need for infrastructure development. For large end-consumers of hydrogen (e.g. industrial clusters) this advantage is diminished.

In sum, the relative competitiveness of hydrogen from electrolysis and natural gas with CCS depends on numerous factors such as scale, infrastructure for transport and storage, assumptions regarding future cost development and availability of cost competitive renewable electricity sources.

2.6.3 Summary hydrogen

The potential volumes of CCS associated with production of low-emission hydrogen in the EU towards 2050 is high, but the uncertainty is also considerable for two main reasons:

- The competitiveness of hydrogen towards other abatement options across all relevant sectors affects the total volume of hydrogen demanded towards 2050.
- The relative competitiveness of hydrogen from electrolysis and hydrogen from natural gas with CCS depends on the trajectory of growth in hydrogen demand, technology and infrastructure development.

Regarding the latter point, the literature indicates that large-scale production of hydrogen from natural gas with CCS is possible at a lower cost than hydrogen from electrolysis in the short to medium term. However, if hydrogen consumption is decentralised (e.g. in transport), the cost of distribution might be higher for hydrogen from natural gas with CCS as it is more dependent on scale to achieve cost reductions than electrolysis. Over time, some studies point out that reduced cost of electrolysis and renewable power generation could make hydrogen for electrolysis increasingly competitive.

Under this uncertainty, it is hard to determine a relevant range for CCS volumes associated with hydrogen production in the EU. As a low estimate, we use the EU Long-term Strategy net-zero emission scenarios. These scenarios foresee an annual hydrogen consumption of 70-80 Mtoe which is only produced as green hydrogen, resulting in 0 tCO_2 captured and stored. As a high estimate, we use

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[97] Assuming an energy loss of 25% related to STR and CCS processes.

[98] Norwegian gas exports stood at 117 bcm in 2017.

[99] EC (2018) – In depth analysis accompanying the A Clean Planet for All

[100] Hydrogen Council (2020) - Path to hydrogen competitiveness A cost perspective

the Steam Methane Reforming Scenario from the Hydrogen Roadmap Europe, which see an annual consumption of hydrogen of 2,175 TWh, implying annual storage demand of 465 $MtCO_2$ in 2050.[101]

Hydrogen - Assessment of interest for CCS - Potential	
Emissions 2017 ($MtCO_2$)	Industrial feedstock: 64-96 $MtCO_2$ (included in other sectors) Expected strong demand growth as energy carrier
CCS important for decarbonisation	Likely, though electrolysis can also be an option
Cost (EUR/tCO_2)	N.A.
Scenario capture 2030 ($MtCO_2$/y)	/
Scenario capture 2050 ($MtCO_2$/y)	0-465
Capturable volume ($MtCO_2$/y) – all Europe	N.A.
Role of CCS	Medium (high potential, high uncertainty)

2.7 Summary of findings for the different sectors

Future deployment of CCS will be strongly dependent on the policy choices and technology development pathways ahead, to be discussed in the following chapters. From the identified sectors, metals, minerals, chemicals, waste, refining, power, heat and hydrogen, the range of technology options for mitigation varies.

For some processes, such as cement production and waste incineration with heat recovery, few mitigation options for deep emission reductions beyond CCS are identified, due to the nature of their processes (calcination processes for cement or incineration of waste). The amount of cement production and waste incineration will depend on factors such as increased use of alternative materials and recycling shares, which will both depend on future policies and economics. The abatement costs of CCS are estimated in the range of 60-120 EUR/tCO_2. for cement and 150-200 EUR/tCO_2 for waste-to-energy. The technical potential for CO_2 captured in cement and waste incineration in the EU are estimated to be around 109 Mt and 59 Mt, respectively.

To reach net-zero emissions in these two sectors, the minimum CCS requirement is estimated to be around 90 $MtCO_2$/y by 2050[102], assuming all other measures are applied. Both cement and waste-to-

[101] JRC (2020) – Hydrogen use in EU decarbonisation scenarios.

[102] The minimum level of capture from cement and waste-to-energy are estimated with the following assumptions:

Cement: production levels equivalent to current levels, renewable energy is used for heating, leaving only process emissions - 57 $MtCO_2$/y fossil emissions. Reduced cement production could reduce emission levels.

Waste-to-energy: fossil waste is in municipal and commercial/industrial waste reduced by 50% from estimated 2035 levels: residual shares from sorting and recycling are held constant with CEWEP estimates for 2035 - 36 $MtCO_2$ fossil emissions.

energy have the potential for relatively large shares of BECCS, which could give negative emissions and compensate for emissions remaining in other sectors.

For other production processes, there are multiple alternative abatement pathways. For iron and steel production, there are emissions associated with different stages of the current production route. While CCS can abate emissions from some of the stages in these routes (with abatement costs of 70-95 EUR/tCO_2), deep emission reductions require investments in entirely new production routes, which could either be dependent on hydrogen or carbon capture. It is unclear if one or both routes would be the preferred pathway towards net-zero emissions, and the industry is currently exploring both. The future cost of hydrogen will strongly impact the choice between the two routes. When the technology is fully developed, direct iron reduction based on green hydrogen is estimated to have lower abatement costs than CCS on existing technologies, depending on electricity prices. A direct smelting route with CCS, when the smelting process is fully developed, is also estimated to have a lower cost than CCS on the existing production route. The potential for CO_2 captured in iron and steel production in the identified pathways range from 11-71 MtCO_2/y, while the technical capturable potential on current production is 69 MtCO_2/y.

In ammonia production, where emissions are primarily associated with hydrogen production, there are multiple possible pathways, both with and without CCS. Again, the abatement costs depend on the hydrogen production method. The abatement cost for ammonia production using steam reforming of natural gas, with CCS, is estimated to be have an abatement cost for ammonia production of 39 EUR/tCO_2, while the abatement cost using green hydrogen is estimated to be in the range of 108-215 EUR/tCO_2.

Petrochemicals can be produced with chemically recycled feedstock or bio-feedstock, and with electricity for heating, but these are associated with significantly higher abatement costs than CCS.

The potential for CCS on chemicals/petrochemicals is estimated to 39 MtCO_2/y but depends on the policies and pathways chosen.

Refineries are estimated to have high abatement costs for application of CCS on certain processes, and even higher for other processes, but alternative measures can be even more costly. The technical volume capturable on refineries is estimated to be about 59 MtCO_2/y.

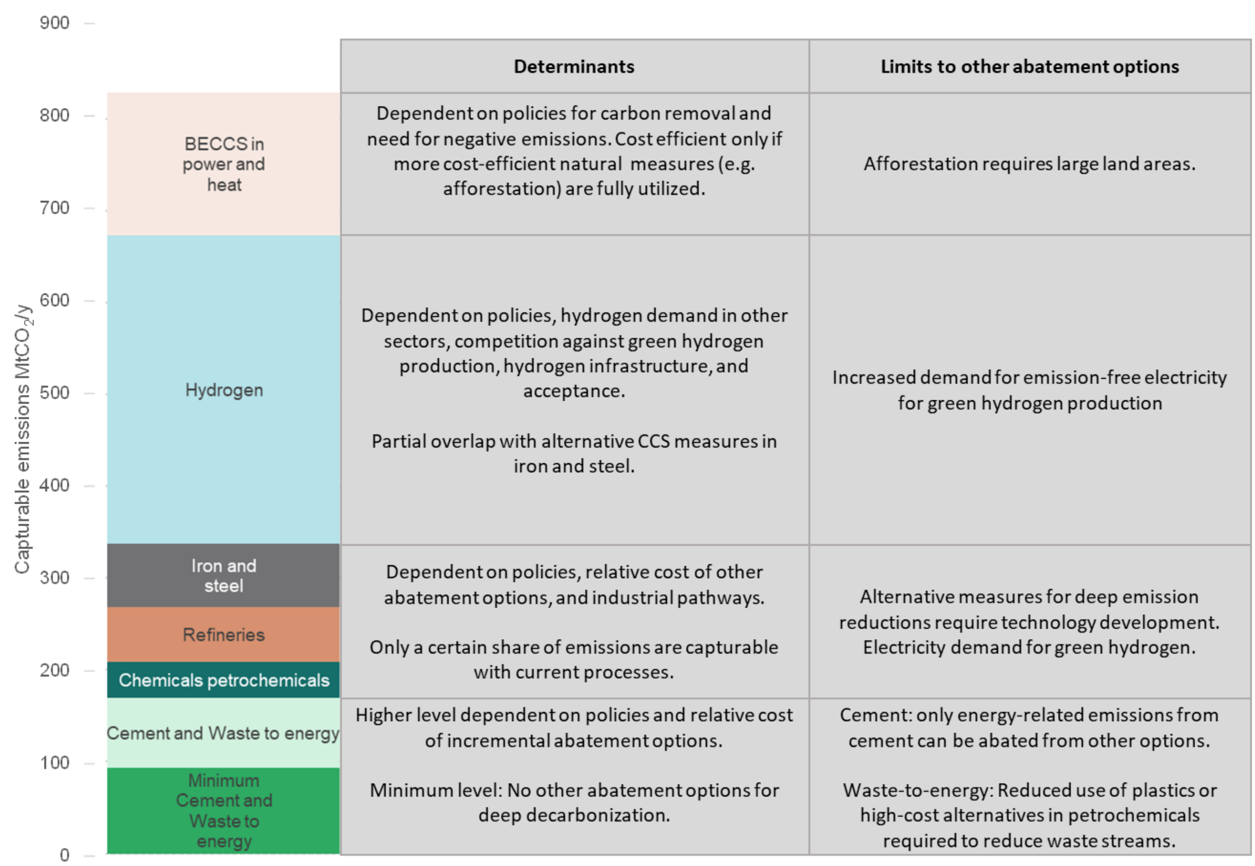
Current CCS abatement costs in the power sector are estimated to between 70 and 105 EUR/tCO_2, with further cost reductions expected. However, CCS in fossil-based power generation is not expected to be an important abatement option in Europe, as the cost of renewable electricity production has plummeted over the last decade. Fossil fuel power plants with CCS could deliver flexibility and/or back-up needed in an electricity system dominated by intermittent renewable electricity generation but would compete with batteries and demand-side flexibility for short-time flexibility needs and with nuclear, bioenergy and hydrogen for longer-term baseload and back-up needs. However, CCS combined with bioenergy (BECCS) could be an important source of negative emissions while at the same time delivering baseload/flexibility. BECCS represents the largest potential upside for the deployment of CCS technologies in the European power sector, with one EU LTS net-zero scenario including 178 MtCO_2 of BECCS in 2050. In this context, BECCS would then compete with other sources of negative emissions such as DACCS and natural sinks such as afforestation.

The most uncertain scope for CCS is associated with hydrogen production. Today, hydrogen is mainly used in some industrial processes. However, hydrogen could play a central role as a zero-emission energy carrier that could enable decarbonisation of numerous activities across the entire economy. How widespread hydrogen will be deployed depends on future cost developments of the various hydrogen production methods as well as alternative abatement options across all relevant sectors. This uncertainty is reflected in different scenarios that provide highly diverging volumes of hydrogen in the EU by 2050. CCS could play a significant role in the production of hydrogen from natural gas, but low-emission hydrogen also can be produced by electrolysis. The relative attractiveness of the two solutions depends on numerous factors, including the availability of cheap renewable sources for electricity generation, technology cost developments, scale economies and whether demand is centralised or decentralised. To reflect the considerable uncertainty, the outcome for hydrogen production with CCS[103] could be in the range of 0-465 $MtCO_2$/y.

Based on these results, we can summarize the potential capturable volumes from each of the reviewed sectors. The total capturable potential in EU28 from all the reviewed sectors is above 800 $MtCO_2$/y, when accounting for overlapping measures (hydrogen usage instead of CCS in the iron and steel sector). This represents the estimated maximum level. The minimum level is estimated to be around 90 $MtCO_2$/y. This minimum level assumes net-zero emissions are achieved in cement (assuming current production levels) and waste-to-energy and includes only process emissions from cement production and emissions from waste incineration with higher recycling rates and lower fossil shares.

The uncertainty within this range is very high, and highly dependent on EU and member state policies, and industrial decisions, discussed in the further chapters. Limitations to use of natural resources for renewable energy production or natural carbon removals can also be important determinants to which alternative abatement measures are possible.

Figure 23: Total annual capturable volume from sectors, and key determinants.



Source: Carbon Limits and THEMA analysis

[103] Not including blue hydrogen production for own use in chemicals/petrochemicals, refineries. These volumes are included under the respective sectors.

Table 8 - Summary all sectors

	Metal	**Mineral**	**Chemical**	**Refining**	**Waste**	**Power**	**Hydrogen***
Emissions 2017 ($MtCO_2$)	115	122	102	130	68	1007	Included in other sectors
CCS important for decarbonization of sector	—	✓	—	✓	✓	✗	—
Cost (Euro/tCO_2)	70-95	100-120 60-89	39 Ammonia /H_2 65-113 Petro-chemicals	40-103 SMR 240-359 other	150-200	70-105	
CCS cost relative to other deep decarbonisation measures	—	✓	✓	✓	✓	✗	—
Relevant for biogenic CO_2 capture	✗	✓	—	—	✓	✓	✗
Scenario capture 2050 ($MtCO_2$/y)	11-71	31-85		10-30		0-218	0-465
Capturable volume ($MtCO_2$/y) – all Europe	69	109	39	59	61	841	
Role of CCS	—	✓	—	—	✓	—	—

The table above presents a summary of the potential scope for CCS in the different sectors for the coming years.

✓ The green checks indicate a favourable situation for CCS

✗ The red crosses indicate an unfavourable situation for CCS

— The orange bars are used when it is unclear whether the situation in the sector will be favourable or not to CCS. It is also used when there are uncertainties which have not yet been lifted.

The cells in which there are no marks or data represent criteria which have not been assessed due, generally, to limited communication from that sector on CO_2 emissions and/or CCS and abatement options more broadly.

It is also important to note that this assessment gives a general view for each sector. Individual projects will not necessarily follow the trend of the sector.

*Hydrogen here is the additional production of hydrogen not already included in the chemical / petrochemical or refining sectors

3. EU policies

In this chapter we analyse how recent developments in EU climate, energy and industrial policies can affect CCS activity in Europe, and thereby the value of the Norwegian full-scale project. Central to the analysis is European Green Deal (EGD). The EGD is a cross-sectoral growth strategy for Europe laying out the intentions and ambitions of the European Commission to tackle the dual challenges of climate change and environmental degradation towards 2050. The EGD is a communication document that is to be followed up by legislative proposals, strategies and action plans. This work is ongoing.

We approach the question of how more ambitious EU climate policies could affect CCS volumes in the EU in three parts:

First, we assess how the role of CCS in the long-term could be affected by the EU raising its climate ambition to net-zero emission for 2050. The degree to which CCS is seen as an important contributor to the EU's long-term emission reduction target should be expected to influence short- and medium-term policies to reduce barriers to the technology's further development and deployment. We assess this question by examining the role foreseen for CCS in the EU's own long-term decarbonisation scenarios as well as pathways compliant with the targets set in the EGD developed by external actors.

Second, we assess key elements of the EU policy mix that could influence the role of CCS in the medium term. As a consequence of the proposed increase in the 2030 climate ambition, the EGD opens most of the EU's current energy, industrial and climate policy framework for revision. We describe and assess the key policy elements that could affect CCS activity in the short- and medium-term. The marginal abatement cost of CCS solutions is above the current EU carbon prices. Therefore, increased CCS deployment can be driven by:

- Measures that increase the carbon prices
- Support schemes for CCS projects
- Measures to ensure that low-emission products and materials can be sold with a premium
- Any combination of the above

To assess whether and to what extent the EGD can be expected to imply a strengthening of these policy drivers in the medium-term policy mix, we focus on five key parts of the EGD:

- Revision of existing climate and energy policies to accommodate an increased 2030 target
- The Industrial Strategy
- The Carbon Border Adjustment Mechanism
- The Hydrogen Strategy and Clean Hydrogen Alliance
- The Circular Economy Action Plan

Finally, we assess how key available financing mechanisms could support CCS projects in Europe in the short term. The four key funding mechanism available for CCS projects are:

- Innovation Fund
- Horizon Europe
- Connecting Europe Facility
- Just Transition Mechanism

In addition, we provide an overview of the potential for CCS support through the recently proposed Recovery Package and describe the role of CCS in the Sustainable Taxonomy framework, significant for the access to private investments funds with a green profile.

3.1 Increased long-term climate ambitions

The proposal to tighten the EU's climate emission target for 2050 from 80-95% reduction[104] to net-zero emissions is a cornerstone of the EGD. In March 2020, the European Commission published its proposal for a Climate Law[105] which makes the net-zero emissions target, in 2050 at the latest, legally binding for the EU as a whole.[106] The proposal is expected to be adopted by both the European Parliament[107] and the EU Council[108].

For the purposes of this report, the key question is how the increased long-term climate ambitions affect the scope for CCS in the short and longer term.

The EGD has not yet been accompanied by updated energy and climate projections or scenarios indicating how the EU expects that a net-zero target could be achieved.[109] Scenarios describing the possible role of CCS in emission reductions presented in the following therefore predated the publication of EGD. Existing long-term scenarios may however shed some light on the role of CCS in full decarbonization scenarios. Relevant scenarios include:

- EC (2018) – A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy
- ICF & Fraunhofer (2018) – Industrial Innovation – Pathways for Deep Decarbonisation of industry
- JRC (2019) – The POTEnCIA Central Scenario – An EU energy outlook to 2050
- JRC (2020) – Towards net-zero emissions in the EU energy system by 2050 – Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal

In the following, each of these documents and their projections for CCS volumes in Europe in 2050 are briefly presented before we discuss the differences.

3.1.1 EC (2018) - Long-term Strategy scenarios

A Clean Planet for All[110] is a communication published by the previous European Commission in 2018, outlining a "strategic long-term vision for a prosperous, modern, competitive and climate neutral economy". The communication mentions CCS as one of seven strategic building blocks to achieve net-zero emissions in the EU, stating that:

"[…] CCS deployment is still necessary, especially in energy intensive industries and – in the transitional phase - for the production of carbon-free hydrogen. CCS will also be required if CO_2 emissions from biomass-based energy and industrial plants are to be captured and stored to create negative emissions. Together with the land use sink, it could compensate for remaining greenhouse gas emissions in our economy."

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[104] Unless otherwise stated, reductions in the following refer to the level in 1990.
[105] EC (2020) - Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation - (EU) 2018/1999 (European Climate Law)
[106] Individual Member States could still have positive emissions levels by 2050.
[107] European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP))
[108] In the conclusions from the meeting it was stated that "[…] the European Council endorses the objective of achieving a climate-neutral EU by 2050, in line with the objectives of the Paris Agreement. One Member State, at this stage, cannot commit to implement this objective as far as it is concerned, and the European Council will come back to this in June 2020." European Council (2019) – European Council meeting (12 December 2019) - Conclusions
[109] While updated scenarios are likely being developed by the Commission, they are as of yet not published.
[110] EC(2018) - A Clean Planet for All - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy COM (2018) 773

As part of the Clean Planet for All Long-term Strategy (LTS), 8 scenarios were developed to explore different pathways towards decarbonisation.[111] Five scenarios (ELEC, H2, P2X, EE and CIRC) achieve an 80% emission reduction in 2050, each scenario with special focus on a certain abatement measure. The focussed abatement measures are electrification, hydrogen and e-fuels, energy efficiency and circular economy. All the five scenarios see increased energy efficiency, transport system efficiency and renewable energy development. A sixth scenario (COMBO) reach 90% emission reduction through a combination of the measures in the five scenarios mentioned above. None of the scenarios have a particular focus on CCS.

Finally, and particularly relevant for the EGD target are two scenarios that achieve net-zero emissions in 2050 (1.5 TECH and 1.5 LIFE). These differ significantly in terms of how emission reductions are achieved:

- **1.5 LIFE** focuses on demand side measures to reduce emissions (e.g. circular economy, lifestyle changes and consumer preferences) and land-use sinks as the key to achieve negative emissions[112].
- **1.5 TECH** focuses on supply-side measures and relies far more on BECCS to achieve net-zero emissions.

The CCS volume results in the LTS scenarios are biased as "[…] limitations in geological storage and transport infrastructure of CO_2" are assumed in the power sector in the 80 and 90% reduction scenarios. These limitations are "partially relaxed" [113] in the net-zero scenarios. For all LTS scenarios, CCS volumes increase post-2050.

The CCS volumes in 2050 associated with each scenario are shown in Figure 24. The most interesting results from this comparison are:

1. Industry emissions are the principal basis for CCS and the total volume of CCS shows limited variation across all scenarios expect for one (1.5 TECH).
2. On average, there is more CCS in the net-zero scenarios than in the 80% emission reduction scenarios. However, the difference between CCS volumes in the P2X scenario (80% emission reduction) and the 1.5 LIFE scenario (net-zero emission) is only 3 $MtCO_2$/y.
3. The higher level of CCS volume in 1.5 TECH is driven primarily by a massive scale up of power sector BECCS. Power sector CCS also increases in this scenario (40 $MtCO_2$) but is still only 22% of the BECCS volume.
4. In all scenarios except 1.5 TECH the power sector contribution is modest; ranging from 0 $MtCO_2$ (EE) to 6 $MtCO_2$ (1.5 LIFE LG).
5. Deployment of CCS in industry sectors starts earlier in the net-zero scenarios, around 2040 as compared to around 2045 in the 80% and 90% emission reduction scenarios.

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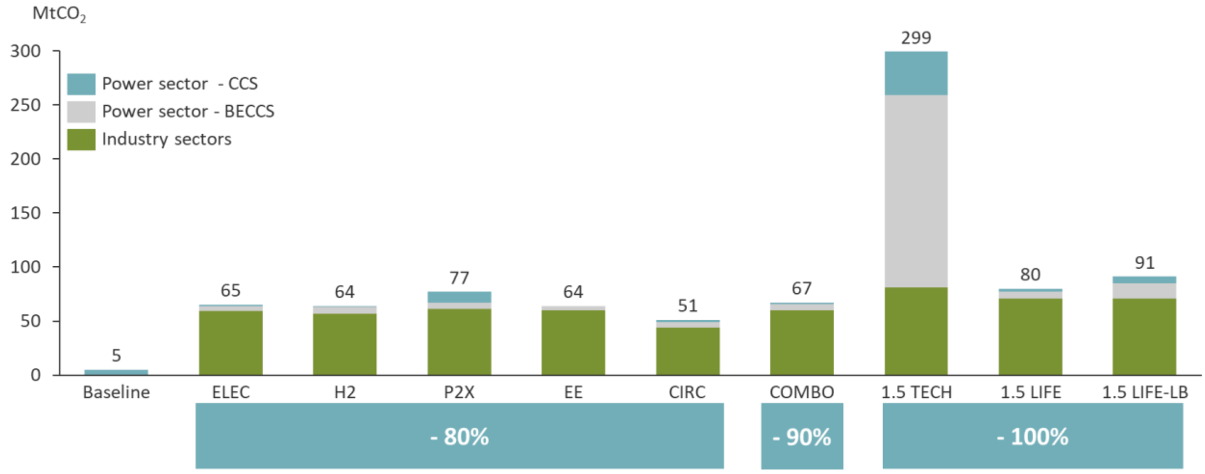
[111] EC (2018) - In-depth analysis in support of the Commission Communication COM(2018) 773

[112] A variation of 1.5 LIFE minimising the use of biomass has also been developed as a sensitivity analyses called 1.5 LIFE-LB.

[113] EC (2018) – In depth analysis accompanying the A Clean Planet for All p. 325

Figure 24 Carbon Captured and Stored Underground across scenarios in the Long-term Strategy scenarios $MtCO_2$/y in 2050[114]



Source: EC (2018)

In addition to the carbon captured and stored (CCS), some of the scenarios see large volumes of carbon capture and usage (CCU) in 2050. The carbon is mainly used to produce synthetic fuels, whereby the carbon is quickly released to the atmosphere. The carbon is therefore mainly captured directly from the air by DACCS technologies, but also some from bioenergy. In the net-zero scenarios, a small volume of carbon is also stored more permanently in materials[115].

The Commission has used stylised carbon prices for the ETS sectors in the modelling of the scenarios. The price increase from €28/tCO_2 in 2030 for all scenarios, to €250/tCO2 in 2050 for the 80% reduction scenarios and to €350/tCO2 in the net-zero scenarios. However, the Commission points out that “real carbon price developments will be different and depend on numerous factors, including the deployment of other policies and how they impact technology costs and deployment.”[116]

The picture drawn from the LTS scenarios does not provide a clear answer as to whether an increased climate ambition of net-zero emissions in 2050 translates into substantially larger volumes of CCS.

3.1.2 ICF & Fraunhofer (2018) – Industrial Innovation – Pathways to deep decarbonisation of industry

ICF & Fraunhofer (2018)[117] developed decarbonization scenarios for European industry towards 2050. They first look at four scenarios where 80% emission reduction is achieved, each emphasising one specific mitigation technology (CCS is one of them) before making two scenarios where all the four mitigation technologies are applied to achieve 80% (mix80) and 95% (mix95). The latter is compatible with a net-zero scenario for the EU.

In the CCS scenario, it is assumed that a large-scale infrastructure for transport and storage of CO_2 is established and that public and political acceptance of CCS is improved. The scenario also relies on

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[114] The scenario descriptions do not explicitly describe how emissions from waste incineration are expected to develop towards 2050 and whether CCS is considered as a source of emission reduction.

[115] The P2X, COMBO, 1.5 Life and 1.5 TECH see CCU being employed, mainly related to DACCS.

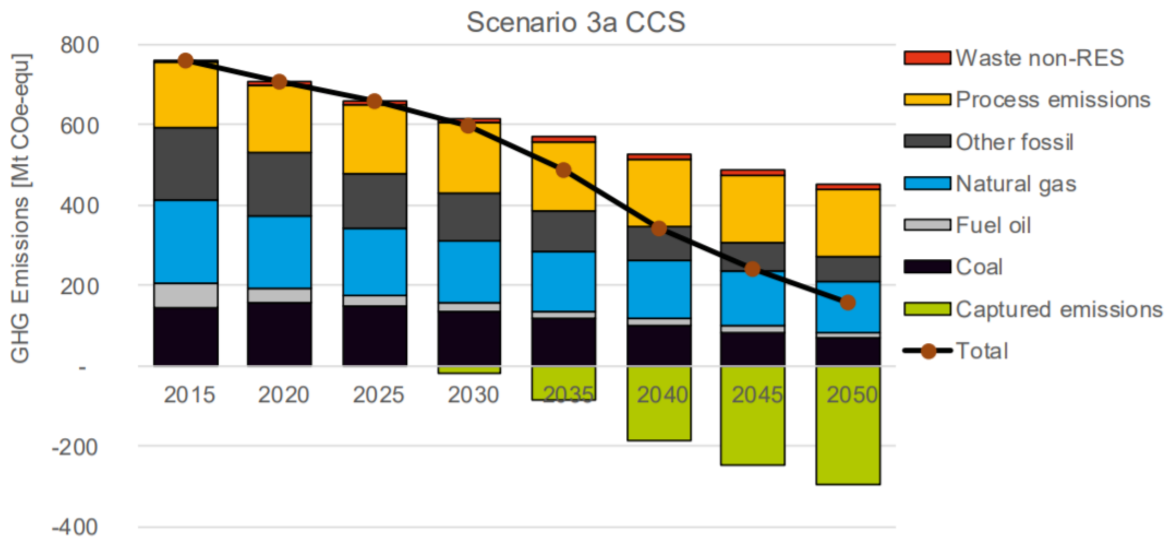
[116] EC (2018) - [In-depth analysis in support of the Commission Communication COM(2018) 773]() – p. 318

[117] ICF and Fraunhofer (2018) - [Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation]().

an economic and political framework that "[…] allows implementation of CCS while maintaining international competitiveness for industries."

Figure 25 shows EU industrial emissions towards 2050 in the CCS scenario. Industrial CCS starts from around 2030, increases to about 200 $MtCO_2$ in 2040 and further to almost 300 $MtCO_2$ in 2050. This is considerably higher than in the EC LTS where CCS from industrial processes only amounted to 81 $MtCO_2$.

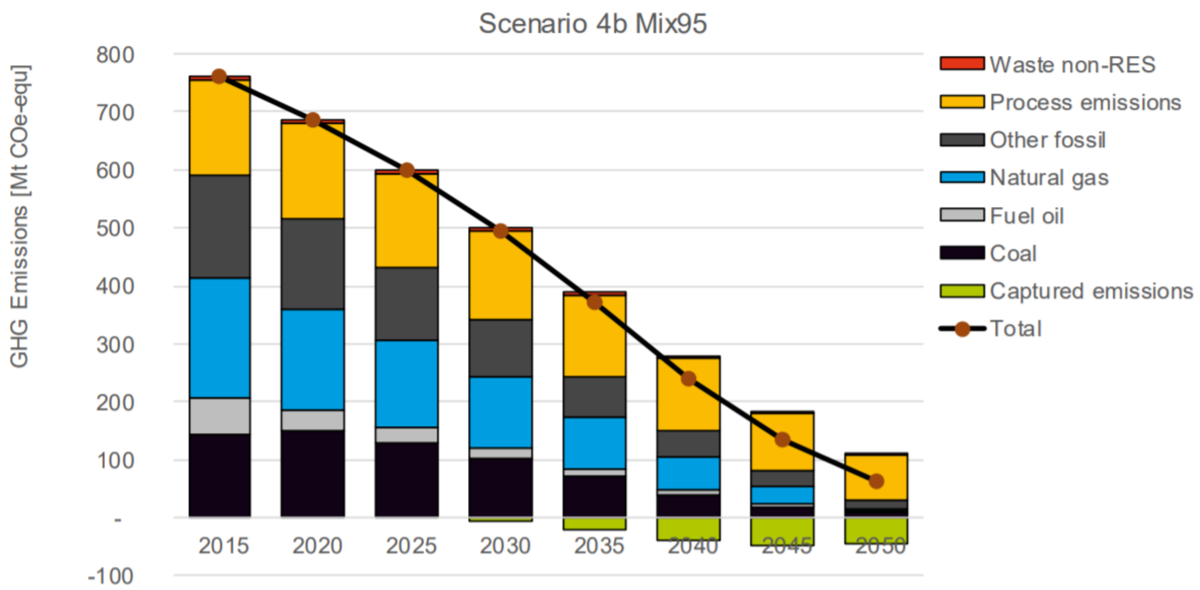
Figure 25: Emissions from European industry in the CCS scenario. $MtCO_2$/y



Source: ICF & Fraunhofer (2018)

Figure 26 shows the results from the Mix 95 scenario. Carbon capture volumes are considerably lower than in the CCS scenario, estimated at less than 10 $MtCO_2$ in 2030, reaching a level of around 40 $MtCO_2$ in 2040 with only a marginal increase by 2050.

Figure 26: Emissions from European industry in the Mix95 scenario. $MtCO_2/y$



Source: ICF & Fraunhofer (2018)

While CCS is used across multiple industrial segments in the CCS scenario, in the Mix95 scenario, it only plays a role to reduce emission from clinker and lime production and refineries as "[…] other major emitters already mitigate emissions via other options."[118]

3.1.3 JRC - The POTEnCIA Central Scenario – An EU energy outlook to 2050 (2019)

The EU energy outlook to 2050[119] produced by the Joint Research Centre (JRC) and using the POTEnCIA model, provides a description of the EU energy system development from 2018 to 2050 given energy and climate policies as they were at the end of 2017[120]. Climate targets for both 2030 and 2050 are missed in this scenario, with emission reductions in 2050 reaching only 53% compared to 1990 levels.

The modelling exercise finds that CCS is employed in the power sector from 2040, covering 8% of total electricity generation in 2050 and capturing 171.5 $MtCO_2$ annually. In the industrial sectors, 168 $MtCO_2$ emissions are captured annually by 2050, mainly from cement manufacturing (81 $MtCO_2$) but even from iron and steel facilities (17 $MtCO_2$). In the scenario, CCS does not start to appear before 2030, with larger volumes captured only from 2040.

The carbon price is expected to increase from around 25 EUR/tCO_2 in 2030 to 121 EUR/tCO_2 in 2050 and is the key driver of CCS deployment in both industrial and power segments. CCS becomes

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118 ICF & Fraunhofer (2018) p. 51 and 52: *This is explained by three main factors: first, alternative production technologies gain large market shares of mostly 100% in all energy intensive sectors (e.g. low-carbon cement, H2-based chemicals and steel). Second, in glass and paper, CCS was not allowed as it is more unlikely in these sectors. Third, renewable electricity and clean gas reduce CO_2 emissions drastically, which leaves little space for additional CCS. Consequently, a major application of CCS is the non-metallic minerals industry, where process emissions are difficult to mitigate. Here, it is mainly lime burning that applies CCS, because alternative mitigation options are not available.*

119 JRC (2019) - The POTEnCIA Central Scenario – An EU energy outlook to 2050

120 It could be characterized as a sort of Business as Usual (BAU) scenario

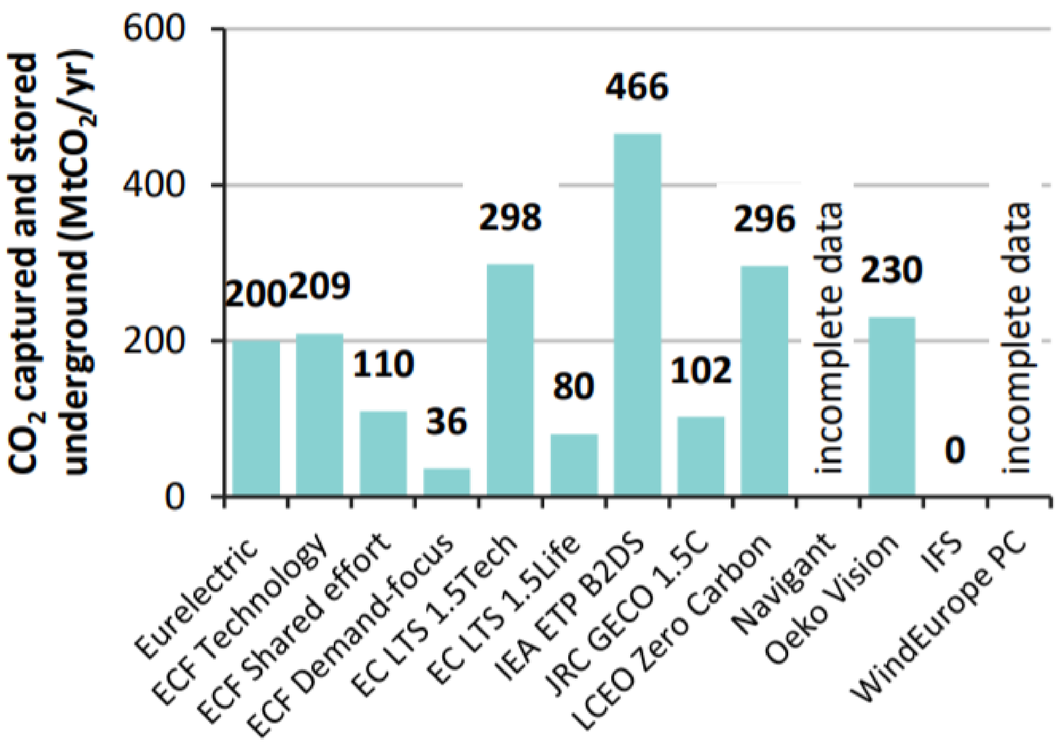
competitive in the power sector beyond 2040 as the carbon price increases. The EUA price is estimated at 72.9 EUR/tCO_2 in 2040, 84.2 EUR/tCO_2 in 2045 and 121.7 EUR/tCO_2 in 2050.

3.1.4 JRC comparison of net-zero scenarios for the EU

The Joint Research Institute (JRC, 2020)[121] compares emission mitigation scenarios from various institutions in line with the increased climate targets put forth in the EGD. The report looks at 8 scenarios that achieve more than 50% emission reduction by 2030 and 16 scenarios that achieve at least 90% emission reduction by 2050.

Figure 27 presents an overview of the role of CCUS across the different scenarios in 2050. While most scenarios rely on CCS to achieve emission reductions in 2050, there is a significant variation in volumes. Six of the 13 scenarios assume CCS volumes above 200 MtCO_2 annually by 2050.

Figure 27: CO_2 underground storage in 2050 in scenarios that meet the EU28 long-term vision[122].



Source: JRC (2020)

3.1.5 Discussion of CCS volumes in scenarios

The scenarios presented above are based on different models and different assumptions and serve different purposes.

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[121] JRC (2020) – [Towards net-zero emissions in the EU energy system by 2050 - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal]()

[122] Note: JRC GECO 1.5C includes power, industry and other; in EC LTS and LCEO Zero Carbon, CO_2 is captured and reused (not shown in the figure). Navigant mentions the need for CCS in steel and cement production, with potential CO_2 supply of 113 and 179 MtCO_2/y, respectively.

The large volumes of BECCS in the 1.5 TECH scenario are driven by the need to offset unabated emissions in the rest of the economy. In the 1.5 LIFE scenario, a greater use of natural sinks and demand-side measures reduce the need for negative emissions from BECCS. Fraunhofer[123] has pointed out that the scenarios lack transparency when it comes to assumed cost of various technologies for negative emissions, which is a key determining factor for efforts to reduce remaining unabated emissions.

It is interesting to compare the results from the JRC Energy Outlook for 2050 with the results from the EU LTS scenarios. While the former sees emission reduction of only 53% in 2050, the volumes foreseen for CCS is higher than in all the decarbonisation scenarios from the EU LTS. While it is hard to compare results across two different modelling exercises, two elements that could potentially explain the difference in CCS results stand out:

- The partial (exogenous) limitations on CCS as an abatement measure in the EU LTS net-zero scenarios
- Barriers to other abatement measures with a lower long-term abatement cost than CCS. These barriers may not be addressed in the Energy Outlook 2050 but are addressed in the more ambitious LTS scenarios.

The results from ICF & Fraunhofer (2018) suggest that while CCS hold the potential to deliver considerable emission reductions in the industrial sectors (CCS scenario), other abatement options can potentially cut a large part of emissions at a lower cost than CCS, leaving only around 40 $MtCO_2$ annually for CCS (Mix95).

3.1.6 Conclusions

Increasing the long-term climate ambition of the EU to net-zero emissions by 2050 means that more expensive abatement options must be deployed. To what extent increased CCS will be the result of the increased ambition, will depend on its competitiveness with other high-cost abatement options. No policy targets for or indications on the expected volumes of CCS needed to achieve this long-term ambition have yet been presented as part of the European Green Deal.

The scenarios developed to explore decarbonisation pathways as part of the Commission's 2018 Long-term Strategy (A Clean Planet for All), preceding the EGD, all see CCS playing a role in cutting emissions in industrial sectors in 2050 (40-80 $MtCO_2$). The scenarios are not, however, conclusive on how the role of CCS *changes* between 80% emission reduction scenarios and scenarios achieving net-zero emissions. In terms of policy direction, the LTS scenarios should be interpreted with caution, as they mainly serve to explore the impact of various decarbonisation options. They do not represent concrete policy measures nor targets for different abatement alternatives. When it comes to the role of CCS in particular, the scenarios are biased due to the application of exogenous limitations explained by acceptability issues and lack of infrastructure.

A review of other scenarios assessing decarbonisation pathways compliant with the EGD ambitions for 2050 is similarly inconclusive. The role of CCS varies considerably across scenarios depending on assumptions on costs, policy preferences, technological development etc.

In conclusion, the scenario review shed little light on the role of CCS as a long-term abatement option. The scenarios do however indicate that the long-term scope for CCS depends on the removal of barriers linked to acceptability and infrastructure, and that the main competing alternatives are electrification, hydrogen and e-fuels, energy efficiency and a more circular economy.

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[123] Fraunhofer (2019) - Assessment of the In-depth Analysis Accompanying the Strategic Long-term Vision "A clean planet for all" of the European Commission

3.2 Policy mix towards 2030

The long-term scenarios suggest that CCS has a role to play towards 2040 and 2050, but there is considerable uncertainty regarding the volumes needed and the trajectory after 2030. In this section we examine EU policies that could drive CCS development in the medium term, i.e. to 2030 by looking at current and proposed policies and strategies. The main focus is on recent changes in the policy framework associated with the EGD.

3.2.1 Raising the 2030 target to 50-55%

The European Commission has announced that it will propose an increase in the 2030 emission reduction target from the current 40% to minimum 50% and potentially to 55%. An impact assessment to provide a basis for a final proposal is currently under preparation. The results from the impact assessment are expected to be published in September 2020.

As part of a revision of the 2030 target, the European Commission will review central parts of the current measures related to emission reductions. The Emissions Trading Scheme (ETS), the Effort Sharing Regulation (ESR), the Energy Taxation Directive (ETD), the Renewable Energy Directive (RED) and the Energy Efficiency Directive (EED) are mentioned specifically.

The revision of the 2030 climate target could be an important driver for CCS activity in Europe through its impact on the market for emission allowances (EUA's). Many of the sectors where CCS is a key abatement measure are included in the Emission Trading Scheme (ETS) and need to cancel EUA's equivalent to annual emissions. The increased ambition for emission reductions by 2030 is likely to lead to an increase in the EUA price, as the linear reduction factor of the ETS is likely to be increased, hence strengthening incentives to invest in abatement measures such as CCS.

Notably, the ETS could be expanded to cover additional sectors. In the EGD, the Commission mentions three sectors – maritime transport, buildings and road transport. While it states that it "[…] will propose to extend European emissions trading to the maritime sector […]", the wording is more undecisive for road transport ("[…] will consider applying emissions trading to road transport […]" and even more so for buildings, where the European Commission states that it will ("[…] launch work on the possibility of including emissions from buildings in European emissions trading […]". This is reiterated in the inception impact assessment (IIA) on the 2030 Climate Target Plan[124].

There is still considerable uncertainty with regards to the scale of the EUA price impact. There are four main reasons for the uncertainty:

- **By how much the 2030 target is increased**: One analysis by the Centre for Climate and Energy Analysis finds that a 50% target would yield prices of 52 EUR/tCO_2 in 2030, while a further increase to 55% would push prices up to 76 EUR/tCO_2[125]. The calculation assumes that the increased reduction effort is allocated proportionally between the ETS and non-ETS sectors.

- **How the increased ambition is allocated between ETS and ESR:** All else equal, the EUA price impact will increase if a larger share of the increased ambition is allocated to the ETS, and vice versa.

[124] EC (2020) – 2030 Climate Target Plan

[125] Compared to a baseline scenario of EUR29/tCO_2 in 2040 with a 40% reduction scenario. CAKE (2020) - European Green Deal impact on the GHG's emission reduction target for 2030 and on the EUA prices

- **Whether and how new sectors are included in the ETS**: The price impact of including new sectors in the ETS depends on the short- and long-term abatement costs of the sector in questions, by how much the ETS cap is increased, and to what extent there are overlapping or supplementing measures to address barriers in the sectors. A proposal on including emissions from the maritime sector is expected, while the possibility to include buildings and road transport will also be discussed: "[…] what are the feasibility and possible implications of adding to emission trading, next to the maritime sector other sectors such as road transport or emissions from buildings as well as the implications for remaining ESR sectors […]".[126]

- **To what extent support measures or sector specific targets are introduced**: Measures aimed to support the realisation of abatement options in the ETS sectors would impact the EUA price. A case in point is the support schemes for renewable electricity production, that have been an important driver for emission reductions in the power sector. The support resulted in lower EUA prices than would have otherwise been the case. The extent to which the European Commission and Member States will use support mechanisms or regulatory measures as "double regulation" for ETS installations towards 2030 is uncertain. However, this will also be discussed in the impact assessment of the 2030 climate target that is expected in September. In the IIA, the European Commission notes that it will present "[…] the type of enabling framework required, for instance related to sustainable finance, R&D&I, the deployment of new technologies at scale, […]".

We expect that the tightening of the 2030 climate target will increase the EUA price and will as such strengthen the EUA price as a driver for CCS deployment. It is unlikely that a target increase would only be achieved in the ESR sectors. By how much the price will increase depends on the target level, how the target increase is allocated between the ETS and ESR, by whether and how new sectors are included in the ETS, and by the extent to which other measures affecting the abatement costs in the ETS sectors are implemented. As is also demonstrated below, it is very likely that such additional measures and targets will be implemented.

3.2.2 Industrial strategy

The European Green Deal emphasizes the need to drive the transition in industrial sectors: "EU industry needs 'climate and resource frontrunners' to develop the first commercial applications of breakthrough technologies in key industrial sectors by 2030. Priority areas include clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilisation."[127]

In March 2020, the European Commission presented "A New Industrial Strategy for Europe".[128] The strategy addresses the need for industrial transformation in light of the ambition of a climate neutral Europe in 2050.

The strategy does not contain much in terms of concrete policy proposals, but points to several upcoming sector-specific strategies and initiatives that could be important for CCS deployment in European industry. There is limited information and detail related to the concrete policies that will be proposed, making it hard to determine to what extent policy measures will be technology neutral or focused on specific abatement options. The key sector-specific strategies mentioned are:

- EU Strategy on Clean Steel: The European Commission "[…] will support clean steel breakthrough technologies leading to a zero-carbon steel making process.".

[126] EC (2020) – 2030 Climate Target Plan

[127] EC (2020) – European Green Deal

[128] EC (2020) – A New Industrial Strategy for Europe - COM(2020) 102 final

- Chemicals Strategy for Sustainability: Focus on protection against hazardous chemicals.
- Strategy on the built environment: The strategy will "[…] address the sustainability of construction products […]".
- Strategy for Sustainable and Smart Mobility

Among the measures to maintain the competitiveness of European industry through this transition is a proposal for a Carbon Border Adjustment Mechanism (discussed in the next subchapter).

The creation of new markets for climate neutral and circular products is also mentioned as one of the EGD objectives. In the EGD roadmap, "Initiatives to stimulate lead markets for climate neutral and circular products in energy intensive industrial sectors" is expected to be developed from 2020. One way of achieving this is by ensuring that consumers are informed on the varying degrees of sustainability of products. If some customer segments have a higher willingness to pay for low-emission products, this could help industries finance emission reducing measures.[129]

In addition, the European Commission points out that the Just Transition Fund will mobilise funds to help carbon intensive regions in transforming their industries. More generally, the European Commission states that the Innovation Fund will help deploy "[…] large-scale innovative projects to support clean products in all energy-intensive sectors.".[130]

The need to focus on energy efficiency and the supply of sufficient amounts of low-carbon energy is emphasised. Three initiatives are especially linked to the latter:

- EU Strategy on offshore energy: Renewable energy is emphasised as a focus area, as it will "[…] help cater for a substantial increase in the amount of electricity required […]". [131]
- Review of the Trans-European Network Energy regulation: To "[…] support the transition to climate neutrality." [132]
- Hydrogen strategy and a Strategy for smart sector integration: Aims to ensure that all energy carriers are used more effectively (discussed below)

The industrial strategy signals EU's intention to support European industry towards low-emission production processes through a combination of support for low- and zero-emission technology development and developing markets where abatement cost can be passed on to the industry's customers. The latter is necessary to prevent carbon leakage as the competitiveness of European industry is exposed to unilateral carbon costs. A successful implementation of policies that enable industry to pass carbon costs on to final consumers would allow for a faster decarbonisation of these sectors than if the transition were to be financed over national budgets.

3.2.3 Carbon border adjustment mechanism

Closely related to the Industrial strategy is the European Commission's pending proposal for a Carbon Border Adjustment Mechanism (CBAM) as an alternative to existing measures to mitigate carbon leakage from European industries.

The proposal is expected to be presented in 2021. Little detail on the design and scope of the CBAM to be proposed are known, but the EGD communication and the initial impact assessment indicate the following:

- The CBAM would initially be applied to selected industries or segments

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[129] EC (2019) – European Green Deal - "Consumer policy will help to empower consumers to make informed choices and play an active role in the ecological transition."

[130] EC (2020) – A New Industrial Strategy for Europe - COM(2020) 102 final

[131] EC (2020) – A New Industrial Strategy for Europe - COM(2020) 102 final

[132] EC (2020) – A New Industrial Strategy for Europe - COM(2020) 102 final

- The CBAM is meant to replace existing measures to mitigate carbon leakage, i.e., free allocation of EUAs and indirect carbon cost compensation
- The CBAM needs to be in compliance with the EU's trade obligations, hereunder the WTO agreement
- Several different policy instruments will be assessed, including a carbon tax on selected products (regardless of origin), a carbon customs duty or border tax, or an extension of the ETS to imports.[133]

From a theoretical perspective, a CBAM has some advantages compared to the current measures to prevent carbon leakage. While existing measures exempt or compensate eligible industry in Europe from (a sizeable part of) direct and indirect carbon costs, a CBAM would add carbon costs to imported products. As a result, the cost of carbon emissions would be more correctly reflected in the industries' product prices in European markets with a CBAM than with current measures and strengthen incentives for substitution to less carbon-intensive products in the end-user markets. Moreover, while the current measures to mitigate carbon leakage implies public spending, a CBAM would impose the carbon cost on market prices.

In practice, the design of the CBAM must resolve three key challenges. Firstly, efficient functioning of a CBAM relies on access to information regarding the carbon content as well as the embedded carbon costs of imported products, neither of which are necessarily easily available nor verifiable in a global market.[134] Secondly, while a CBAM would protect European industry from import competition, it would not relieve it from the impact on export competition unless a negative CBAM would apply to exports[135]. Last, but not least, there is a risk that the implementation of a CBAM will be perceived as in breach with the WTO framework, which could cause politically motivated trade retaliation, harming European exporting industries.

Whether the European Commission succeeds in its efforts to design an efficient and acceptable proposal for a CBAM will have ramifications for the other elements of EU's industrial policy. A successful application of a CBAM, implying pass-through of carbon costs to end-user markets and less dependence on public funding, should reduce uncertainty and make European industry more willing to invest in long-term abatement solutions. Public funding mechanisms would still be necessary to remove and reduce barriers associated with R&D and infrastructure development, but these could become more potent if the industry itself would take a more proactive role in development and implementation of abatement solutions.

However, as it is not clear that the design challenges described above will be resolved, considerable uncertainty regarding future European carbon leakage policies remain.

3.2.4 Hydrogen strategy

Hydrogen is expected to play an important role in the decarbonisation of the European economy. The Commission writes that the "[…] Green Deal identified clean hydrogen as a priority area where the EU needs climate and resource frontrunners to develop such technologies and commercial applications.

[133] EC (2020) – Inception Impact Assessment on the Carbon border adjustment mechanism.

[134] This problem is exacerbated if the CBAM is to apply not only to raw materials (e.g. steel), but also to products containing the raw materials (e.g. cars). If a CBAM where to only apply to the raw materials, the risk of carbon leakage in other parts of the value chain would increase. The problem is also likely to be more challenging for industries dominated by indirect emission costs than for direct emission costs, as there is no definitive way of determining the emission factor in the electricity factor that could be applied to all producers globally.

[135] Or e.g. if compensation or free EUA are given in relation to the share of production exported.

This also builds on the Commission's 2018 Long-Term strategy, "A Clean Planet for All", which highlights the critical role that hydrogen can and must play in achieving climate neutrality."[136]

As part of the EGD, the Commission has initiated work on an EU hydrogen strategy, a Clean Hydrogen Alliance, as well as an EU strategy for smart sector integration. These documents and initiatives are expected to provide important signals of the future development of hydrogen production and consumption in the EU in the coming decades.

As described in chapter 2, hydrogen is an alternative abatement option to CCS in several sectors. Thus, targeted support and mechanisms to enable hydrogen as a preferred abatement option by the EU increase the competitiveness of hydrogen vis-à-vis CCS in these sectors.

On the other hand, CCS can be applied to capture up to 90–95% of emissions from hydrogen production based on natural gas and coal. A more significant role of hydrogen in the European economy could therefore potentially lead to increased demand for CCS. However, as hydrogen can also be produced without CCS technologies (electrolysis is the main alternative, see chapter 2.6), the extent to which EU hydrogen policies facilitate the development of other production methods is also important for expected demand for CCS in hydrogen production.

The Hydrogen strategy, the Clean Hydrogen Alliance and the Strategy for energy sector integration are all expected to be published/launched on July 8, 2020, and the final documents are therefore not available as references for this report. Below we provide a short description of what is known about these initiatives at the time of writing.

In a communication document on the pending **Hydrogen strategy**, the Commission emphasises that support for hydrogen produced by electrolysis will be the priority[137], but that blue hydrogen can play a role in a transition phase to "[…] support the effective scale-up of renewable hydrogen by contributing to satisfy medium-term demand for hydrogen." The term 'clean hydrogen' covers both green and blue hydrogen.[136]

A leaked version of the hydrogen strategy, published by Euractiv on June 22, provides some indication as to the content of the final document.[138] Some key points for the leaked draft (that must be cross-checked with the final version of the strategy) are:

- The strategy prioritizes hydrogen produced by electrolysis based on renewable electricity, reserving the term 'clean hydrogen' for this production method.
- Considerable cost reductions are assumed possible for 'clean hydrogen' until 2030.
- The Commission will propose criteria for certification of renewable hydrogen. The details of the certification criteria is not defined, but it should be "[…] taking into account also already existing industry initiatives to set up hydrogen guarantees of origin for renewable and low-carbon hydrogen" referring to the CertifHy initiative (see also chapter 2.6).
- Specific targets for electrolysis capacity and production are set for 2024 (4 GW electrolysis) and 2030 (40 GW electrolysis). This translates into investment needs of €13–15 bn. for electrolysers and €50–150 bn. for new renewable electricity generation capacity, amounting to 50-75 GW.

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[136] EU Commission (2020). Inception Impact Assessment Clean energy – an EU hydrogen strategy. Retrieved from: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12407-A-EU-hydrogen-strategy

[137] They write that "The initiative will focus on supporting the deployment of renewable hydrogen (also referred as 'green') as a priority."

[138] Euractive (2020) – Leaked draft of the European Commission's Hydrogen strategy.

- Hydrogen from natural gas with CCS is termed 'low-emission fossil-based hydrogen' and is perceived to play a role in retrofitting of existing fossil-based hydrogen production. The strategy cites a study by Navigant[139] asserting that 50% of existing hydrogen production in the EU can be retrofitted with CCS by 2030 (corresponding to 190 TWh hydrogen and about 40 $MtCO_2$[140]) and indicates investment needs of €1–6 bn. of investment for such retrofitting until 2030.
- Support schemes are deemed key to develop hydrogen demand. Several mechanisms are discussed, including a carbon contract for difference (CCfD) on the ETS price, competitive auctions and minimum quotas of low-emissions hydrogen. Though not explicitly stating that the CCfD would be available for hydrogen from natural gas in CCS, it is mentioned that it could be applied at a pilot stage for the replacement of existing hydrogen production, where retrofitting with CCS is mentioned as a key solution earlier in the strategy.

An association consisting of industry, public authorities and civil society called the **Clean Hydrogen Alliance** is expected to be launched at the same time as the hydrogen strategy. In the Industrial strategy, the Commission writes that the Alliance "[…] will build on existing work to identify technology needs, investment opportunities and regulatory barriers and enablers.". According to the leaked hydrogen strategy draft, the Alliance "[…] will play a crucial role in facilitating and implementing the actions of the Strategy and in particular its investment agenda." More specifically the leaked draft states that "Through interlinked, sector-based CEO round tables and a policy-makers' platform, the Alliance should support scaling up production and demand for renewable and low-carbon hydrogen, coordinate action, and provide a broad forum to engage civil society."

A **Strategy on energy system integration** is also expected to be published alongside the Hydrogen strategy. The objective of the strategy is to "[…] strengthen the necessary links across different sectors in our energy system, and to use every opportunity to reduce emissions. This integration of our energy system is necessary if we want to achieve a deep but also cost-effective decarbonisation of our economies.". The strategy is expected to outline how the different parts of the energy system (e.g. electricity system, gas system) should be linked to exploit synergies.[141]

A somewhat more detailed summary of key aspects of the draft Hydrogen strategy is provided in Box 5. Strong conclusions should however not be made based on the document as the final version may well differ significantly from a leaked draft. Although the draft may indicate the direction in which the European Commission wants to go, the political feasibility plays a role, too. It is also important to bear in mind that the final strategy document will need to be followed by concrete legislative proposals to be approved by the Member States and the Parliament, meaning that the final result might also differ from the indicated targets in the final hydrogen strategy document.

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[139] Navigant (2019) – The optimal role for gas in a net-zero emissions energy system. Retrieved from https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

[140] Assuming 0.24 $MtCO_2$ pr. TWh of hydrogen produced from natural gas with CCS. Calculated from https://ec.europa.eu/jrc/sites/jrcsh/files/final_insights_into_hydrogen_use_public_version.pdf

[141] EC (2020) - Preparing a future EU strategy on energy sector integration

Box 5 - Description of key aspects of the leaked draft Hydrogen strategy

Hydrogen strategy (Leaked draft)

The draft document sees "[…] large-scale deployment of clean hydrogen at a fast pace is key for the EU to achieve a higher climate ambition, reducing greenhouse gas emissions by minimum 50% and towards 55% by 2030, in a cost effective fashion."

New terminologies for hydrogen of different origins are introduced: 'Renewable hydrogen' is used for hydrogen produced by electrolysis based on renewable energy sources. Hydrogen from natural gas or coal with CCS is labelled 'Fossil-based hydrogen with carbon capture'. The term 'Low-carbon hydrogen' cover both above categories, while 'clean hydrogen' is only used for 'renewable hydrogen'.

The cost of renewable hydrogen is assumed to fall rapidly from €2.5-5/kgH2 to €1.1-2.4/kgH2 in 2030. The cost of low-carbon fossil-based hydrogen starts from a lower level today (€2.5/kgH2) but costs are is not seen to fall substantially by 2030 (€2.2-2.5/kgH2). Fossil-based hydrogen without CCS is estimated to cost €1.5-1.7/kgH2. In areas with good renewable resources, renewable hydrogen is competitive with fossil-based hydrogen in 2030

The Commission will propose criteria for certification of renewable hydrogen. The details of the certification criteria is not defined, but it states that it could be based on a "[…] wider terminology and certification framework of other renewable fuels" and "[…] taking into account also already existing industry initiatives to set up hydrogen guarantees of origin for renewable and low-carbon hydrogen" referring to the CertifHy initiative.

The strategy prioritises 'Renewable hydrogen' in general and from solar and wind power in particular as these solutions are "[…] the most compatible option with the EU's climate neutrality goal in the long term […]". However, it also sees a role for 'low-carbon fossil-based hydrogen "[…] primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen. The document indicates the following targets:

Short-term (2024): Annual production of 0,5-1 Mt of renewable hydrogen (4 GW of electrolyser capacity). Electrolysers should be located next to existing demand centres for hydrogen. Further, "[…] existing hydrogen production plants should be decarbonised by retrofitting them with carbon capture and storage technologies and manufacturing of electrolysers […]".

Medium-term (2030): Annual production of 5-10 Mt of renewable hydrogen (40 GW electrolyser capacity). Without stating it as a target, the strategy also cites a study by Navigant suggesting that 50% of existing fossil-based hydrogen production could be retrofitted with CCS by 2030. Industry and transport are the two key market segments. Cumulative investments of €13-15 bn. for electrolysers, €50-150 bn. for 50-75 GW renewable electricity generation and €1-6 bn to retrofit existing fossil-based hydrogen production facilities with CCS is foreseen by 2030. Considerable investments are also needed for infrastructure and end-user side adaption.

Long-term (2030-2050): Renewable hydrogen technologies reach maturity and is widely deployed to decarbonise sectors where other abatement options are not available or too expensive such as aviation or some building segments. The strategy underlines the need for a massive increase in electricity production. Replacing natural gas with biogas in hydrogen production facilities with CCS is mentioned as an option for negative emissions.

Policy: To ensure that these targets are reached, the strategy underlines the need to develop a hydrogen market framework and incentivising supply and demand including by "[…] bridging the cost gap between conventional solutions and renewable and low-carbon fossil-based hydrogen and through appropriate State aid rules." In addition, the document mentions the development of framework conditions enabling the development of gigawatt-scale wind and solar plants dedicated to hydrogen production.

The strategy states that "With the need to scale-up renewable and low-carbon hydrogen before it is cost-competitive, support schemes are likely to be required for some time". One potential supply-side instrument suggested is a carbon contracts for difference (CCfD) to cover the gap between the EUA price and the strike price. A pilot scheme for a CCfD is suggested to replace existing hydrogen production in the industry as well as to produce fuels for the maritime sector. Other potential measures mentioned are quotas or minimum share of low-carbon hydrogen in specific sectors. For renewable hydrogen, market-based support schemes in the form of competitive tenders is also mentioned as an option.

3.2.5 Circular Economy Action Plan

The Circular Economy Action Plan[142] is one of the key elements of the EGD. The aim is to continue the development towards an economy which minimise the need for raw material extraction and waste generation through a wide set of measures. Measures for increased circularity can be an alternative abatement measure to CCS in cases where it aims to reduce the demand for industrial emission-intensive products.

An element of the Circular Economy Action plan that could be important for CCS deployment, is a proposal for a regulatory framework for carbon removals, expected in 2023. The EU LTS sees the combination of bioenergy and CCS (BECCS) as a key technology to provide negative emissions, and holds that a framework to ensure that such efforts are considered in the EU's climate policy framework is needed.

In the Action Plan, the European Commission focus on natural carbon removals as well as the use of CO_2 (CCU) "[…] for instance through long term storage in wood construction, re-use and storage of carbon in products such as mineralisation in building material."[142]

As the proposal for a framework for carbon removal is not expected until 2023, it is not likely to be a substantial driver for BECCS in the short term. How the framework will weigh carbon removals through usage vs. underground storage could, however, be important for the long-term demand for CCS to achieve negative emissions.

3.2.6 Conclusions

In essence, the main potential drivers for the realization of CCS projects in the 2030 perspective are increased carbon prices, support schemes, and an increased willingness to pay for low-emission products in markets. In addition, the competitiveness of CCS towards other high-cost abatement measures plays a significant role. The policies accompanying the EGD and the outcome of the current policy revisions are crucial for the development in these drivers in the short to medium term.

In general, as ESR targets and ETS caps are tightened, the marginal abatement cost increases. Important challenges that the policy framework has to tackle when emission reduction targets are tightened, are the design of efficient policies in sectors where emissions are hard to abate and the prevention of carbon leakage from European industry as carbon costs increase.

A premise for this assessment is also that the EU is expected to prefer a system where the marginal abatement cost is equal or at least similar among sectors, and where the ETS plays the cornerstone role it was meant to play.

Carbon prices: Most of the sectors where CCS is considered an important abatement option (see chapter 2) are included in the ETS and thus exposed to the EUA price. If the emission reduction target is increased to between 50 and 55%, EUA prices are set to increase and could increase significantly, depending on the mix of policies:

- Allocation of the reduction target: With a proportional reduction in the cap, one study shows EUA prices increasing to between 52 and 76 €/ton (assuming 50% and 55% respectively). If the increase in effort is disproportionally allocated, it is likely that more is allocated to the ETS, thus increasing the EUA price additionally.
- Expansion of the EU ETS: The inclusion of sectors from which emissions have proven to be hard to abate is considered as part of the 2030 target revision. An inclusion of the maritime

[142] EC (2020) – Circular Economy Action Plan - COM(2020) 98 final

sector, road transport and/or buildings is therefore likely to imply a higher EUA price as additional abatement is likely to be cheaper in current ETS sectors than in the new ones.

- Additional policies: The application of additional policies such as support schemes and infrastructure investments are likely to reduce marginal abatement costs both in existing and potential new ETS sectors. The evidence from policy and strategy documents published so far, indicates that policies directed at industry abatement and green hydrogen are likely to be implemented.

Carbon leakage: Higher carbon prices improve the business case for CCS as well as other abatement measures in the affected sectors. However, the extent to which the Commission can rely on high carbon costs to drive decarbonisation of industrial sectors depends on whether it can simultaneously establish effective measures to prevent carbon leakage. The CBAM proposal is central in this effort as it could ensure that the carbon costs can be passed onto final consumers in Europe. However, significant design challenges must be overcome to ensure that the mechanism can function as an efficient measure to prevent carbon leakage.

Measures to increase the end-user's willingness to pay for low-carbon products can be both a supplement and an alternative to a CBAM mechanism. We do, however, not consider it likely that such policies will have a major impact on carbon leakage in the short-term horizon.

Hence, carbon leakage concerns are likely to impact the extent to which the EU will let an increased EUA price alone drive increased emission cuts in the 2030 timeframe. The difficulty in passing on carbon costs in product prices, increases the likelihood that a tightening of emission targets will be accompanied by targeted support schemes.

Support schemes: If carbon prices are not sufficient to drive decarbonisation of the industrial sectors, support schemes will be needed to drive CCS development. While the EU is clearly stating that it will support the development of decarbonisation technologies in industries where CCS is an important abatement option, no concrete CCS policies have yet been proposed as part of the EGD.

On the other hand, the leaked version of the Commission's Hydrogen strategy clearly indicates a willingness to support hydrogen production as a means to cut emissions in industrial sectors as well as the development of additional renewable electricity production to source green hydrogen production. The potential role of CCS and blue hydrogen in the transition period remains to be seen in the final version of the strategy document (expected on July 8), but additional policies to stimulate green hydrogen would clearly put a downward pressure on the carbon price.

The only explicit mention of a potential targeted support for CCS projects in the medium term can also be found in the Hydrogen strategy draft. The draft seems to indicate a Contract-for-Difference that could support mechanism for retrofitting existing steam methane reformation facilities with CCS technologies among the suggested measures for decarbonization in industry. If implemented, this could be one of the key policy instruments to develop CCS in the EU in the coming decade.

At the time of writing (June 2020), the uncertainty relating to the medium-term policy mix of the EU is considerable, making it challenging to predict how it might affect CCS developments. The EUA price is set to increase due to more ambitious policies, but the EU is likely to implement or extend policies to dampen price increases in order to mitigate carbon leakage, e.g. through various support schemes. In the next section we take a closer look at the main support schemes and to what extent CCS projects can be expected to benefit from these.

3.3 EU funding available for CCS development

Although the general EU climate policy framework does not explicitly favour CCS, the main support mechanisms for emission abatement mechanisms are open to funding of CCS. In this section we assess to what extent available funding mechanisms are likely to facilitate CCS projects.

According to the Zero Emission Platform, the main EU funding tools for CCS projects are

- Horizon Europe
- The Innovation Fund
- Connecting Europe Facility (CEF) for Energy projects

These instruments are relevant for different parts of the CCS value chain. While Horizon Europe applies to research and development projects and thus supports earlier stages of the technology development cycle, the Innovation Fund offers support to demonstration projects. The CEF applies to more mature concepts by aiding the scale-up and roll-out of infrastructure projects.

The Global CCS Institute also lists the following financing streams as relevant for CCS (and other decarbonization technologies): Sustainable Finance Taxonomy, European Investment Bank, and the Just Transition Mechanism (JTM).

More funding through the proposed EU Recovery Package to deal with the impacts of the Covid-19 pandemic, through its focus on EGD-aligned stimulus, could result in further CCS support.

3.3.1 Horizon Europe

Horizon Europe is an ambitious EUR 100 billion research and innovation programme and the successor of the research program Horizon 2020. According to the Zero Emission Platform, Horizon Europe will be “a key funding mechanism for climate technologies, including carbon capture.”[143]

The strategy for Horizon Europe is under development. In December 2019, the document “Orientation towards the first strategic plan for Horizon Europe” was published. The orientation identifies six main clusters of research areas. CCUS is included in cluster 4: Digital, Industry and Space and cluster 5: Climate, Energy and Mobility.

The orientation refers to the Horizon Europe proposal[144] which identifies a number of research and innovation priorities within the fields of climate, energy and mobility, including cross-sectoral solutions for decarbonization. CCUS is one of 5 solutions described as part of the need to develop cost-efficient, net-zero emission energy systems centred on renewables. Research on the development of carbon capture, utilisation and storage (CCUS) solutions for the power sector and energy-intensive industries, is called for. Reference to CCS associated with the transitory role of blue hydrogen is also explicit:

> “Carbon Capture, Utilisation and Storage is a CO_2 emission abatement option that holds great potential for the power sector and especially for industries with high process emissions. It is also an important technology that allows the production of large volumes of near-zero carbon (‘blue’) hydrogen and other synthetic fuels from natural gas until sufficient renewable (‘green’) hydrogen and synthetic fuels becomes available.”[145]

According to the orientation document, a partnership approach to the projects is recommended, and a number of examples of relevant partnerships is mentioned. In addition, the orientation holds that a candidate European Partnership on a Geological Service for Europe would contribute to this cluster by providing expertise and data services in areas of energy storage and carbon capture storage.

Horizon Europe is to be launched January 1st, 2021. The Mission Boards have released draft reports proposing concrete targets and timelines at the end of June 2020 with final recommendations

143 https://zeroemissionsplatform.eu/about-ccs-ccu/eu-policy/. Zero Emission Platform (ZEP) is the technical adviser to the EU on the deployment of CCS and CCU – a European Technology and Innovation Platform (ETIP) under the Commission’s Strategic Energy Technologies Plan (SET-Plan).

144 2018/0225 (COD)

145 2018/0225 (COD)

expected by the end of September. These will then be reviewed and selected by the Commission and launch as part of Horizon Europe in 2021.

3.3.2 Innovation Fund

The Innovation Fund is presented as a key funding instrument for delivering the EU's economy-wide commitments and one of the world's largest programmes for demonstration of innovative low-carbon technologies.

The total value of the fund is estimated to EUR 10 billion from 2020–2030 depending on the EUA price, as it is funded by revenues from EUA auctions.

The fund has identified five focus areas:

- Innovative low-carbon technologies and projects in the energy-intensive industry
- Carbon Capture and Usage
- Construction and operation of CCS
- Innovative RES generation
- Energy storage

The first call for grants under the innovation fund is scheduled for 2020 with an estimated budget of EUR 1 billion and new calls will be issued successively. The fund offers financing for highly innovative technologies and will focus on big flagship projects with European value added. However, unlike NER300, which it succeeds, small-scale projects, defined as projects with capital costs below EUR 7.5 million, and energy-intensive industries are also eligible for grants from the Innovation Fund.

The fund can finance up to 60% of the innovation in a project, and up to 40% can be paid out before the project is completed, subject to the achievement of predefined milestones.

Funding from the Innovation Fund can be combined with funding from a host of other sources, such as InvestEU, Horizon Europe, Enhanced European Innovation Council (EIC) pilot, InnovFin Energy Demo Projects, NER300, Connecting Europe Facility, Modernization Fund and Cohesion Fund, national programmes and private capital.

3.3.3 Connecting Europe Facility

The Connecting Europe Facility (CEF) is an EU funding instrument to support targeted infrastructure projects at European level. In order to be eligible for grants under the CEF, a project needs to be included in the TEN-E (Trans-European Energy Networks) framework and have status as Projects of Common Interest (PCI). Generally, PCIs must serve the purpose of helping the EU establish an internal energy market that is integrated, secure, competitive and sustainable. Within the TEN-E policy, nine corridors have been identified, with carbon dioxide networks being one of the prioritised areas: "(D)evelopment of carbon dioxide transport infrastructure between Member States and with neighbouring third countries in view of the deployment of carbon dioxide capture and storage."

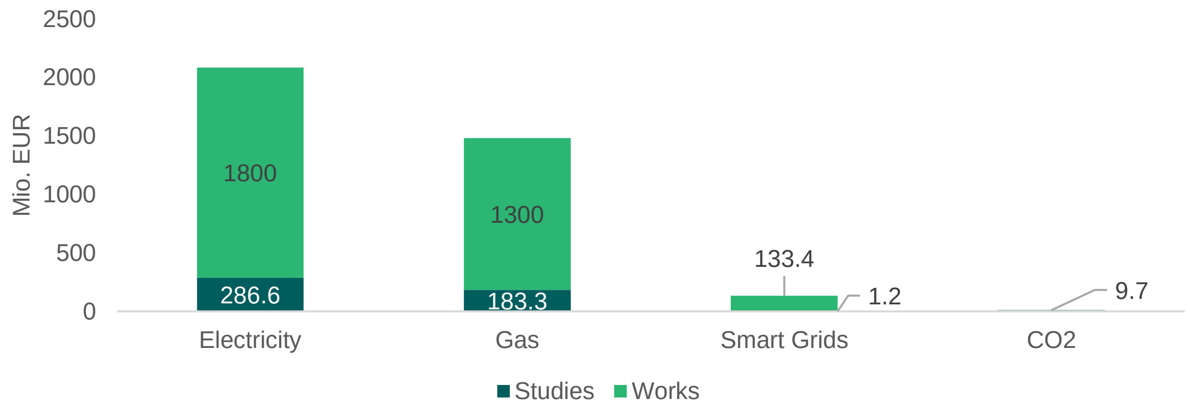
The TEN-E regulation, first adopted in 2013[146], is under review in order to ensure consistency with the 2050 climate neutrality objective. In the combined evaluation roadmap / Inception Impact Assessment, informing citizens and stakeholders about the European Commission's work on the intended initiative,

[146] Regulation (EU) No 347/2013, OJ L, 25.4.2013. The TEN-E Regulation sets out criteria for establishing the projects of common interest ("PCI") necessary to implement the priority corridors and thematic areas. It also sets a framework to facilitate the timely implementation of these PCIs, provide a framework for cross-border allocation of costs and incentives of PCIs and determine the conditions for Union financial assistance for the PCIs.

the European Commission writes that part of the objective of the review is to "…foster the deployment of innovative technologies and infrastructure, such as […] networks for hydrogen and other carbon neutral/renewable gases, carbon capture, storage and utilisation, and energy storage."

From 2014 to 2020, EUR 4.6 bn. were allocated to the CEF fund for energy. In the next budget period 2021–2027, EUR 8.7 bn. is earmarked for CEF, corresponding to approximately 1.1 billion EUR/y.

Figure 28: CEF funding for ongoing EU Projects of Common Interest



Source: EU Commission, Innovation and Networks Agency (2020). Connecting Europe Facility – Energy: 2020 Key Figures[147]

Currently, 138 active actions to support the implementation of 96 ongoing PCIs receive EUR 3.8 bn. of CEF Energy funding. As can be seen in Figure 28, EUR 2.1 bn. is allocated to electricity infrastructure (67 actions), EUR 1.5 bn. to gas infrastructure (65 actions), EUR 134.5 m. to smart grids (4 actions), while studies related to CO_2 networks (3 actions) receive EUR 9.7 m. from the fund.

In the latest call for proposals that closed on 27 May 2020, 28 proposals were submitted, cf. Table 9. The requested budget totalled EUR 3.4 bn. while the available budget is restricted to EUR 980 m. The allocation of funds will be published in October, 2020. The CO_2 network requests for funding could only come from the 5 projects included in the 4th PCI list[148].

Table 9: Budget requests for 2020 CEF Energy funding call

Sector	Proposals received	Requested budget	Available budget
Electricity	13	EUR 2.6 billion	
Gas	6	EUR 334.6 million	
Smart Grids	1	EUR 186.4 million	
CO2 networks	8	EUR 240 million	
Total	**28**	**EUR 3.4 billion**	**EUR 980 million**

[147] https://ec.europa.eu/inea/sites/inea/files/cefpub/cef_energy_key-figures-2020-web.pdf

[148] These projects are the CO_2-Sapling Project for building the transportation infrastructure for the Acorn CCS project, the CO_2 TransPorts initiative (Rotterdam, Antwerp, North Sea Port) in the Netherlands and Belgium, the Northern Lights project, the Athos project in the Netherlands and the Ervia project in Ireland. https://ec.europa.eu/energy/sites/ener/files/c_2019_7772_1_annex.pdf

Source: European Commission (2020).[149]

3.3.4 Recovery package

The European Commission’s proposal for a Recovery Package[150] for the EU in the aftermath of the Covid-19 crisis, consists of EUR 1,850 billion shared between an increased long-term EU budget (EUR 1,100 billion) and a new recovery instrument, Next Generation EU, consisting of EUR 750 billion borrowed from financial markets.

The European Commission aims for the package to accelerate Europe’s green and digital transitions. There is no support earmarked for CCS or hydrogen, but both technologies would likely be eligible for funding through many of the support mechanisms. The most important are perhaps:

- **European Recovery and Resilience Facility** (EUR 560 bn.): To be spent by Member States in line with the objectives of the European Semester, with special emphasis on measures that support the green and digital transitions. The funding will be available for all Member States, but with a special focus on those hit hardest by the crisis.
- **Just Transition Fund increase** (EUR 40 bn.)
- **InvestEU increase** (EUR 15.3 bn.): Support for investment in sustainable infrastructure
- **Strategic Investment Facility** (EUR 15 bn.)**:** Support for green technologies. Meant to stimulate additional private investments.
- **Horizon Europe increase** (EUR 94.4 bn.): Support for climate-related research and innovation activities highlighted together with health.

3.3.5 Just Transition Mechanism

The Just Transition Mechanism (JTM) introduces new instruments under the EGD with the purpose of compensating the regions most affected by the energy transition, i.e. coal- and carbon-intensive regions. The details of the mechanism and the areas that can be eligible for such compensation are not clear yet. The JTM consists of three pillars of financing, the Just Transition Fund, funded via the long-term EU budget, a dedicated just transition scheme under InvestEU, and a public sector loan facility with the involvement of the European Investment Bank. The facility will include EUR 1.5 billion in grants from the EU budget and up to EUR 10 billion in loans from the European Investment Bank's own sources.

A leaked draft of the Just Transition Fund Regulation includes a possibility for facilities covered by the ETS (e.g., steel, cement) to be able to receive support for substantial emission reductions, for example through CCS.

The three pillars are expected to mobilise at least EUR 150 billion of investments in the EU economy over the period 2021–2027.

3.3.6 Sustainable taxonomy framework

As part of the EU Action Plan on Sustainable Finance[151], a Taxonomy for Sustainable Finance (Taxonomy) has been developed over the last few years. The purpose of the Taxonomy is to provide detailed screening criteria to assess the sustainability of different activities. For financial institutions and large companies in the EU, it will be mandatory to report on the ‘sustainability’ of their portfolio in

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[149] https://ec.europa.eu/inea/en/news-events/newsroom/almost-3.4-billion-requested-cross-border-energy-infrastructure-projects

[150] EC (2020) - Europe's moment: Repair and Prepare for the Next Generation - COM(2020) 456 final

[151] COM(2018) 97 final

accordance with this framework from 2021. As a result, investments deemed 'sustainable' are expected to have easier access to financing.

The Taxonomy operates with six environmental targets[152]. In order to be deemed 'sustainable', an activity must give a substantial contribution towards at least one of the targets while at the same time do no significant harm (DNSH) towards any of the other targets.

The screening criteria for each activity will be reviewed over time as best practices and new technologies evolve. In March 2020, criteria for 70 different activities regarding two targets (Climate change mitigation and Climate change adaptation) were published by a technical working group.[153] Technical screening criteria for the remaining four targets are expected in 2020. From 2021 (for the two first) and 2022 (for the four latter), the Taxonomy will be mandatory for reporting from financial institutions and large companies in the EU.

The Taxonomy describes detailed criteria for CCS applied in various sectors, including power production, industrial processes and production of hydrogen, as well as in transport and storage of CO_2. It is specified that:

"Carbon capture and sequestration (CCS) is a key technology for the decarbonisation of Europe. It is included in all pathways presented by the European Commission in its Long-Term Strategic Vision document and is relied upon heavily in three-out-of-four scenarios outlined by the IPCC in the Special Report on 1.5 Degrees."[154]

If CCS enables another activity to operate in accordance with the relevant technical screening criteria, it is Taxonomy eligible.[155] The ability to categorise CCS-related activities as sustainable under the Taxonomy framework is important for access to financial resources from public and private investors.

3.3.7 Conclusions

All the key EU financing instruments are open to applications for funding of different parts of the CCS value chain, although none of them earmark funding for CCS. Notably, however, carbon dioxide networks are one of three prioritized thematic areas within the TEN-E regulation and eligible as projects of common interest (PCI) which is a prerequisite for funding under the Connection Europe Facility. In addition, carbon capture, storage and use are two of the five focus areas for the new Innovation Fund, the EUs main instrument for demonstration of innovative low-carbon technologies. The availability of funding for CCS projects thus indicate that CCS is by no means written off as an important alternative to achieve carbon neutrality in the long-term and cut emissions towards 2030.

It is too early to ascertain to what extent the framework for support to CCUS will be strengthened due to the EGD, but there are no signs of the opposite. For example, as part of the EGD, a Just Transition Mechanism to compensate regions most affected by the energy transition is established. While the final details are not clear yet, it appears that CCS as a measure to cut emissions in industry will be eligible under the JTF.

Table 10 provides an overview of the funding mechanisms and qualitatively assesses their relevance concerning CSS projects.

[152] Climate change mitigation; Climate change adaptation, Sustainable and protection of water and marine resources; Transition to a circular economy; Pollution prevention and control; and Protection and restoration of biodiversity and ecosystems.
[153] EU Technical Export Group on Sustainable Finance (2020) – Technical Annex to Taxonomy: Final report of the Technical Expert Group on Sustainable Finance
[154] Technical annex to the TEG Taxonomy report p.289
[155] See appendix 7.2 for more details on the criteria related to CCS.

Table 10: CCS funding from European financing instruments

Funding source	Orientation	Total available funding	Assessment of funding potential for CCS projects
Horizon Europe	Broad support mechanisms for R&D in new technologies	EUR 100 bn. from 2021 to 2027	CCS pointed to as one suitable technology for decarbonisation in 2 out of 6 main research clusters. No earmarking of funds
Innovation Fund	Innovative low-carbon demonstration projects	EUR 10 bn. from 2020 to 2030, depending on the EUA price	Out of 5 focus areas, 1 apply to CCS, 1 to CCU, and 1 to low-carbon solutions in energy-intensive industry. No earmarking.
Connecting Europe Facility – Energy	Cross-border energy infrastructure projects	EUR 8.7 bn. from 2021 to 2027	Carbon dioxide networks one of four dedicated funding areas. Five CCS projects eligible as PCIs. No earmarking. Currently €10 mln. of a total of €3.8 bn. to CO_2 infrastructure projects. Latest call (2020) sees funding applications for CO_2 network projects totalling €240 m. (of €3.4 bn. in total)
Recovery Package	Accelerate Europe's green and digital transitions	EUR 750 bn. (with almost EUR 350 bn. being spent in 2021, according to a leaked Commission budget proposal)	No direct support outlined in the released documents but CCS likely eligible under several of the proposed initiatives
Just Transition Mechanism	Projects in carbon-intensive regions particularly hit by EGD policies	EUR 150 bn. (2021–2027) with EUR 40 bn. reserved for the Just Transition Fund	Draft indicates possible support for CCS to reduce emissions in heavy industry (steel, cement etc.)

4. Plans and Policies in Selected Countries

4.1 Overview

EU policies and ambitions are complemented by national policies and plans, which are important determinants of the future extent of carbon capture and storage. In this chapter, nine countries are investigated with focus on CCS policies: Belgium, Denmark, Finland, France, Germany, Ireland, the Netherlands, Sweden, and the United Kingdom. These countries all have different industry and emission structures. They vary greatly in terms of amount of emissions and geological opportunities for CO_2 storage.

The countries have been selected based on their location (accessibility to CO_2 transport and storage at Norwegian Continental Shelf), emissions, and/or likelihood of being early movers on CCS. The selected countries and emissions are listed in Table 11.

Table 11: Greenhouse gas emissions and CO_2 emissions from large stationary sources[156] (>100 ktCO_2/y) for countries of focus

Country	Total GHG [MtCO_2e]	Large stationary sources CO_2 emissions [MtCO_2]
Belgium	89.1	44.4
Denmark	80.5	8.7
Finland	53.6	43.0
France	342.2	109.3
Germany	766.8	425.7
Ireland	59.4	15.6
Netherlands	177.3	94.9
Sweden	53.2	49.1
United Kingdom	391.5	145.0

Source: Eurostat and E-PRTR – 2017 data

The country reviews presented in this section are for a large part based on National Energy and Climate Plans (NECP) for the period from 2021 to 2030 which each EU member state has been obliged to prepare. The NECPs should specify how each state intends to address emission reductions, energy goals, interconnection infrastructure and research and innovation. A draft version was due by the end of 2018 and the final version by end of 2019. As of June 2020, some member states have not yet submitted their final plans. In addition to the NECP a number of other public sources have been used, as well as interviews. Amongst the countries of interest, only Ireland and the UK have not submitted the final version of their NECP. For those two countries, draft versions of the NECPs and other documents from the authorities have been reviewed.

Policies related to climate targets and ambitions, CCS, BECCS, hydrogen and CO_2 storage are reviewed. The capturable emissions and storage opportunities are also assessed.

[156] Germany, Finland, Netherlands, Sweden and the UK report emissions from biomass in the E-PRTR database. The others do not.

Box 6 - Calculation of capturable CO_2 quantities in countries

Calculation of capturable CO_2 quantities in countries

To calculate capturable quantities, we have used emission data reported for 2017 from every large (above 100 000 tCO_2/y) facilities in the EU28. The emission data is processed, and sector specific factors are used to calculate the CO_2 quantities which can be captured from each facility. For each country, a low and high capturable CO_2 has also been determined based on the sector overview in chapter 2.

To estimate a low capturable quantity for each country, we have calculated the country's capturable CO_2 emissions from the sectors where CCS is considered to be essential to achieve net-zero emissions, i.e. cement production and waste-to-energy. As seen in chapter 2, if these two sectors are to reach net-zero emissions without ceasing production, CCS is necessary.

To estimate a high capturable quantity for each country, we have calculated capturable CO_2 emissions from large iron and steel, chemical/petrochemical, and refinery facilities in each country, in addition to cement and waste-to-energy. For certain countries with explicit interest for CCS on power generation (UK) or BECCS (Sweden), we have also added these to capturable emissions.

Since the distance to a seaport can determine the cost of transporting CO_2 from a facility to a ship-based transport solution, the distances have been calculated for each facility. The sites are also processed based on location and distance from the closest seaport for goods.

As seen in chapter 2, the range of possibilities of hydrogen production with CCS remains wide and uncertain. On the country level, we do not take captured CO_2 volumes from future hydrogen production for other industry use into account, since it is uncertain where such plants would be located.

Throughout this chapter, details on the different countries, their policies and foreseeable future for CCS, and hydrogen is described. At the end of each country's chapter, a summary table provides an overview of the country information. In the final two rows in the table, we have assessed the overall significance of CCS in the country and the overall relevance for Norwegian storage, based on our assessment of the likelihood of a country to implement CCS and possible volumes of captured CO_2 for Norwegian storage. There are three possible rankings: low, medium and high. Text in green depicts a situation which is favourable to CO_2 storage on the Norwegian Continental Shelf. Text in red shows an unfavourable situation, text in orange describes a situation which is currently undefined but could go both ways and text in grey relates to a lack of information or an unclear situation.

Box 7 - Clusters

Clusters

There are different ways to look at CCS projects in terms of geographical distribution. In this report, projects were studied from a country perspective as it is more relevant from a policy point of view. It could also be interesting to conduct further studies on the possibility of developing CCS clusters. Setting up projects in areas where there are several large emitters can be interesting both financially and in terms of infrastructure. Several capture sites, which can be on different sides of a border or along the same waterway, can benefit from the jointly developing and building of infrastructure as it facilitates their development and can help lower costs. Assembling emissions from nearby sources in a single hub also allows for transport to a storage site, either by ship or pipeline, and storage on a larger scale. Several such cluster projects are currently being studied in the selected countries: Ervia in Ireland, CO_2TransPorts between Belgium and the Netherlands, CO_2 Sapling Transport and Infrastructure Project between the Netherlands, Norway and the UK, the Dunkirk CO_2 Cluster in France or Athos in the Netherlands.

CSLF Task Force on Clusters, Hubs, and Infrastructure, T*ask Force on Clusters, Hubs, and Infrastructure and CCS Update 1, period March 2019 – March 2020,* April 2020

4.2 Belgium

4.2.1 Emissions and CCS potential

Large emission sources in Belgium emitted a total of 98 $MtCO_2$ in 2017. By 2030, Belgium is planning to reduce its emissions by at least 35% compared to 2005-levels in non-ETS sectors. Its target for 2050 is to reduce emissions by 80% compared to 1990.

Belgium's capturable CO_2 emissions[157] in comparison to their total greenhouse gas emissions are illustrated in Figure 29, below. The entire rectangle illustrates the total GHG emissions. The blue box represents the high capturable quantity in Belgium, based on the assessment in chapter 2. The orange rectangles represent emissions which could technically be captured, but where capture is considered difficult or uneconomic. Finally, the grey rectangles illustrate emissions which cannot be captured, such as emissions from transport or non-CO_2 emissions.

[157] Capturable CO_2 emissions - See Box 3 - Capturable volumes

Figure 29: Overview of GHG emissions and CCS Potential - 2017 Data –Belgium

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions
Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

The capture potential represents 14% of the Belgium's GHG emissions based on 2017 values.

Limited research has been conducted on suitable CO_2 storage sites in Belgium. According to theoretical estimates, there are some aquifers and coal veins, mainly in the Campine and Hainaut regions, which could potentially store a few hundred $MtCO_2$.[158] No further studies have been conducted to refine those estimates. Nonetheless, based on these theoretical figures and their uncertainty, it is clear that the storage is likely insufficient to cover national needs and that partnerships for storage in other countries would be necessary. For a country with very limited storage potential, the realisation of capture projects is dependent on the timeline of storage projects which can receive third party volumes.[159]

4.2.2 Plans and Policies

CCS and BECCS

The Belgian government has not announced a detailed plan or target for CCS/BECCS but several projects are currently under way in the country. Overall, the Belgian authorities seem favourable to carbon capture, with an emphasis on usage of CO_2 for industrial purposes. This could be linked to Belgium's limited storage potential. The federal government has supported research projects linked to CCS. The creation of a CO_2 network/infrastructure for transport and temporary storage of carbon with permanent storage abroad is considered. The Flemish Agency for Innovation and Entrepreneurship

[158] Baele J-M., *Stocker le CO2 en sous-sol: une autre voie pour reduire les emissions atmospheriques*, Service de Geologie fondamentale et appliquee – Faculte Polytechnique de Mons, 2008

[159] Interview with Port of Antwerp

has also set up grants for different climate research projects, including CCS. The Flemish government has also supported the feasibility study for some CCS projects in Flanders (Ghent, Antwerp) and will likely pursue its support as projects are further developed.

No mention is made of BECCS in Belgium's national climate and energy plan.

Hydrogen

In their national climate and energy plan, Belgium discusses hydrogen as an essential measure to reduce GHG emissions. The need for further research on the feasibility of transitioning the existing natural gas network into a hydrogen network is mentioned, as well as an increase in storage capacity. No precise figures on potential or future demand are presented and the suggested measures remain at a more theoretical/research level. The NECP also remains very vague on the production route of hydrogen and does not specify whether it could come from electrolysis (green hydrogen) or SMR/ATR (blue hydrogen).

Flanders positions itself as a future hub for hydrogen given its geographical location and its existing transport network, including harbours and pipelines. Again, no precise plans for the development of a network or use of hydrogen have been presented by the Flemish authorities.

Brussels presents hydrogen as an option to reduce emissions from the transport sector and Wallonia states that it supports the industrial deployments of batteries and hydrogen resulting from innovation, by participating in European Common Interest Programs. Specific costs, budgets or emissions reductions linked to hydrogen are not available.

Table 12 – Summary of information for Belgium

CCS is part of the national plan	Yes
Possibility to store in country	Possible, but has not been studied and very limited potential
Low capturable volume ($MtCO_2/y$)	4
High capturable volume ($MtCO_2/y$)	14
Interest for Norwegian storage	Industrial actors recognize the need to store CO_2 in Norway
National support mechanisms in place for CCS	No
CCS deployment timeline	
Government position towards CCS	Recognizing the need but not pushing for it
Public acceptance for CCS	No recent study on the topic identified
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**High**

4.3 Denmark

4.3.1 Emissions and CCS potential

In 2017, facilities with large emissions were responsible for 7.4 $MtCO_2$ in Denmark. Denmark's new Climate Act includes a legally binding target to reduce greenhouse gas emissions (compared to 1990 levels) by 70% in 2030 and to reach net-zero emissions by 2050 at the latest. Denmark has one cement plant, two refineries and three waste-to-energy plants with emissions over 100 $ktCO_2$/y. Together, the capturable emissions from these plants are estimated to be 2.9 $MtCO_2$/y. The capture potential represents 7% of the Danish GHG emissions based on 2017 values.

Figure 30: Overview of GHG emissions and CCS Potential - 2017 Data – Denmark

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

In Denmark, there are several onshore and offshore geological structures (saline aquifers) which could be suitable for CO_2 storage and located throughout most of the country. According to a theoretical assessment, they could, in total, store up to 16,500 $MtCO_2$.[160] CO_2 could also potentially be stored in depleted offshore gas fields.

4.3.2 Plans and Policies

CCS / BECCS

In their NECP, Denmark mentions that further research is required on CCS and that it has set up partnerships for the funding of such research with, for example Nordic Energy Research. No specific

[160] Karen Lyng Anthonsen, Thomas Vangkilde-Pedersen & Lars Henrik Nielsen, *Estimates of CO_2 storage capacity in Europe,* Geological survey of Denmark and Greenland

plans for CCS projects or captured volumes to meet the 2030 or 2050 emissions targets are mentioned. CCS, beyond research aspects, does not appear in the Danish National Energy and Climate plan. More recently, the Danish government has expressed its intention to further develop CCS, with projects starting from 2024 and is expecting to capture and store 0.3 $MtCO_2/y$ from 2030. For this they will set up a market-based financing targeting CCS specifically. This financing will start in 2024 with about DKK 200 million and gradually ramp up to reach DKK 815 million by 2029. The same document also underlines the necessity for negative emissions, including BECSS, from 2050 at the latest.[161] [162]

Hydrogen

Hydrogen, and more specifically green hydrogen, plays an important role in Denmark's NECP. It is expected to serve as a significant method to store renewable energy and enhance security of supply. In 2017, the Danish government allocated EUR 5.1 million for R&D and demonstration programs for hydrogen and fuel cells. In 2019, funds of DKK 128 million were allocated to two specific hydrogen projects which have the ambition to demonstrate production and storage of hydrogen at a large scale. The energy needed for the electrolysis will come from three new offshore wind farms. The Danish government recently published a document highlighting again the importance of green hydrogen in its decarbonization strategy.

Table 13 - Summary of information for Denmark

CCS is part of the national plan	CCS is only mentioned as a research topic, is not mentioned as a technology to implement for emissions reduction
Possibility to store in country	Yes –large potential for onshore and offshore storage (16 500 Mt) but limited studies
Low capturable volume ($MtCO_2/y$)	2
High capturable volume ($MtCO_2/y$)	3
Interest for Norwegian storage	Interest for CCS, but access to own storage
National support mechanisms in place for CCS	Annual marked-based financing of 400 million DKK has been announced
CCS deployment timeline	0.4 $MtCO_2/y$ by 2025 0.9 $MtCO_2/y$ by 2030
Government position towards CCS	Positive, has recently communicated a lot on this and set up financing opportunities
Public acceptance for CCS	No recent study on the topic. Previous Nordjyllandsværket project met strong public opposition linked to storage.
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**Medium**

161 Dansk Regeringen, *Faktaark: Sætte skub i de nye grønne teknologier (PtX og CCS),* May 2020

162 *Klimaaftale for energi og industri mv. 2020,* June 2020

4.4 Finland

4.4.1 Emissions and CCS potential

Large emitters in Finland were responsible for 43 MtCO_2 in 2017, 23 of which origin from biomass. By 2035, the country aims to be carbon neutral. Finland has two cement plants, one large waste-to-energy facility, two refineries, two iron and steel facilities and a petrochemical plant. Together these represent less than 4 MtCO_2/y. Biogenic emissions from the paper and pulp industry could increase the capturable potential to 20 MtCO_2/y. This capture potential represents 25% of the Finnish GHG emissions based on 2017 values.

No suitable geologic formations for the storage of CO_2 have been identified in Finland.[163]

Figure 31: Overview of GHG emissions and CCS Potential - 2017 Data – Finland

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

4.4.2 Plans and Policies

CCS / BECCS

Finland has the intention of reaching climate neutrality mainly by phasing out fossil fuels from electricity production and relying on forests and soil as carbon sinks. CCS is not mentioned as a way of reducing CO_2 emissions in Finland's national energy and climate plan.

Hydrogen

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[163] Koljonen, T., Siikavirta, H., Zevenhoven, R. and Savolainen, I., *CO_2 capture, storage and reuse potential in Finland,* 2003

Hydrogen is not mentioned a in Finland's national energy and climate plan.

Due to limited interest for CCS, the overall significance of CCS in Finland is considered as low. If CCS were to happen, it is unlikely that the limited capturable volumes would play a significant role for Norwegian storage.

Table 14 - Summary of information for Finland

CCS is part of the national plan	No
Possibility to store in country	No suitable geologic formations
Low capturable volume ($MtCO_2/y$)	1
High capturable volume ($MtCO_2/y$)	4
Interest for Norwegian storage	No own storage but limited interest for CCS
National support mechanisms in place for CCS	No
CCS deployment timeline	
Government position towards CCS	Neutral
Public acceptance for CCS	No recent study on the topic.
Overall significance of CCS	**Low**
Overall relevance for Norwegian storage	**Low**

4.5 France

4.5.1 Emissions and CCS potential

France has the 3rd most emissions among the EU member states. Large emission sources in France emitted 109 $MtCO_2$ in 2017. In March 2020, France submitted its national energy and climate plan to the EU[164]. This document is based on two national documents: the pluriannual program for energy (PPE) and the low carbon national strategy (SNBC). The SNBC is France roadmap to reach carbon neutrality by 2050. For 2030, France has a 37% emission reduction objective compared to 2005 (without LULUCF). The zero-emission goal in 2050 is for metropolitan France.

Moreover, France, in 2023, should publish a pluriannual program for climate detailing priorities of investments for climate for the next 5 years[165].

Figure 32: Overview of GHG emissions and CCS Potential - 2017 Data – France

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

The capture potential represents 10% of the French emissions based on 2017 values. France is considering a 3% contribution of CCS to reach net-zero by 2050. The current NECP overuses biomass compared to its potential. Therefore, CCS could be an interesting option to reach net-zero if sufficient emission reductions cannot be attained through biomass.

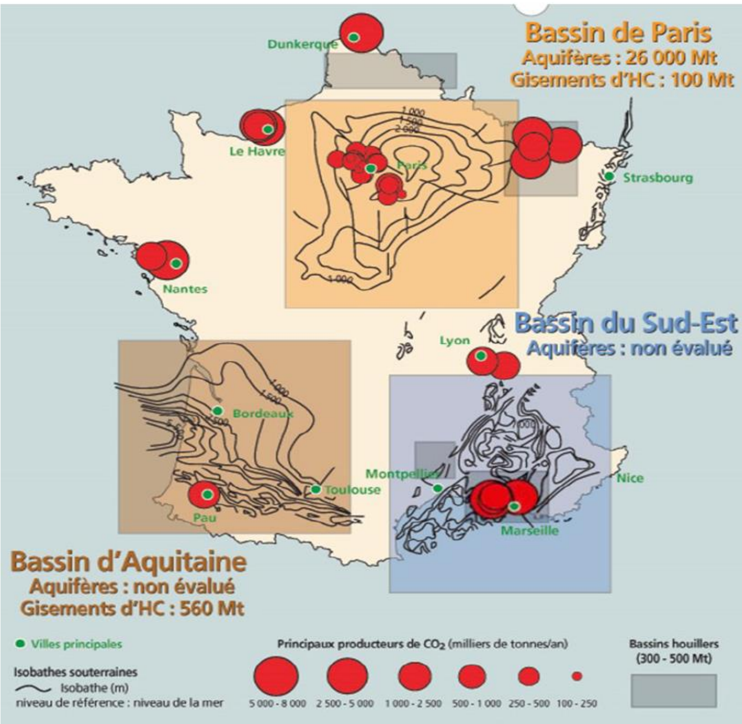
[164] Plan national intégré énergie-climat de la France – March 2020

Stratégie Nationale Bas Carbone – March 2020

[165] Information from ADEME interview

France has 3 main sedimentary basins in which CO_2 storage (onshore) would be possible in saline aquifers (Parisian Basin, Aquitaine Basin, South East Basin and Provence). In addition, there is potential in depleted, or soon to be depleted, hydrocarbon fields in two basins (Parisian Basin, Aquitaine Basin). The BRGM estimated, in a first approach, the CO_2 storage potential of France at around 1 to 1.5 $GtCO_2$. However, the geological storage potential of CO_2 in France is still poorly known onshore and unknown offshore (Atlantic coast, Mediterranean). Storage in the North Sea is an envisaged possibility.[166]

Figure 33: CO_2 sources and storage locations in France -



Source: SNBC 2020

4.5.2 Plans and Policies

CCS / BECCS

In their national energy and climate plan, France has set 2 targets for CCS by 2050: 6 $MtCO_2$/y in the industry, as well as about 10 $MtCO_2$/y in energy production from biomass. One of the figures in the plan shows that CCS could be applied from 2030 and onwards. According to discussions undertaken with ADEME[167], the scenario was developed based on the abatement potential of each technology but not considering the abatement costs. Furthermore, CCS was the last technology taken into account to reach the neutrality objective. The National Plan highlights the need for additional research and innovation in CCUS. Previously, national support for research and innovation for renewable energy, CCUS, energy storage averaged about 500 million EUR/y. No specific support for CCS deployment is specified in the plan.

Many sectors (including Construction, Mines-Metallurgy) have identified CCS as a means to reach carbon neutrality in the roadmaps currently under development. If CCS is identified in the roadmap, the

[166] Stratégie Nationale Bas Carbone – March 2020

[167] French environmental and energy management agency

Directorate General for Enterprise (under the Ministry of Economy and Finance) might support the deployment of CCS.

Arcelor Mittal in Dunkirk is planning to send captured volumes of 1 $MtCO_2$/y to Norway by 2030 and is currently seeking national support to undertake engineering studies[165].

Two sites considering CCS are planning to send applications to the first call of the Innovation Fund[165]. CCS might be deployed earlier and at a larger scale than presented in the national energy and climate plan in France. Funding might be released by the government but is not yet in place.

In addition, Le Havre wants to relaunch their CCS activities and highlighted the need for a CO_2 storage location in the North Sea.

BECCS is an option presented to achieve negative emissions and ensure carbon neutrality in 2050. There is however no current known project considering this technology for power generation.

Hydrogen

In the national plan, the focus for hydrogen is on electrolysis and hydrogen storage in salt caverns. While the plan acknowledges that steam methane reforming could be key for large consumers of hydrogen, for distributed use, electrolysis is considered to be the preferred technology.

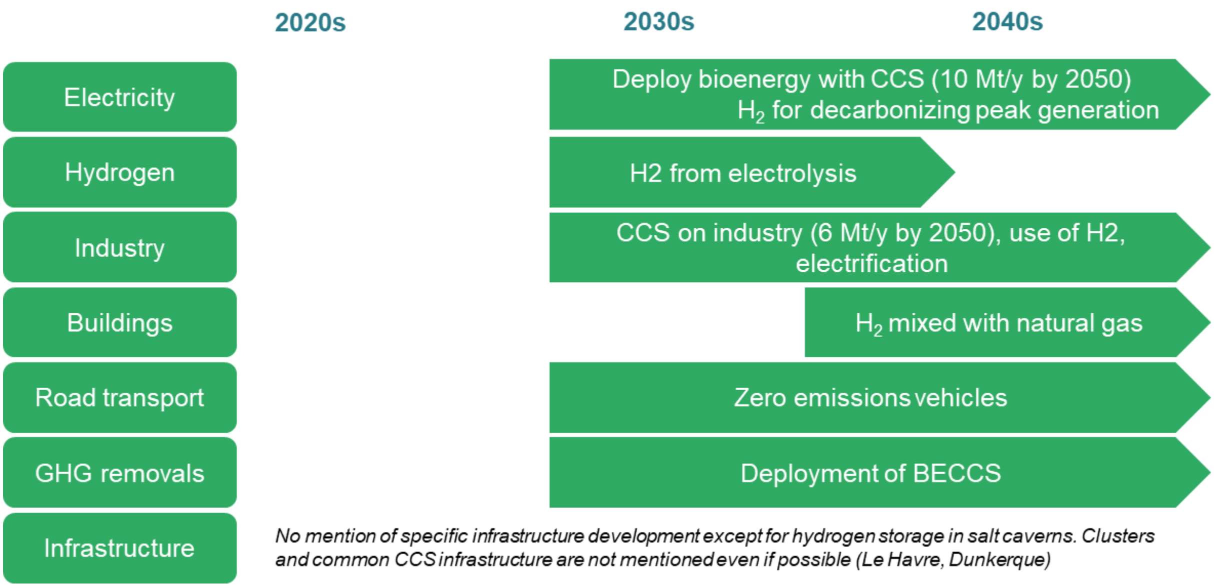
Hydrogen is planned to be used for mobility, primarily in heavy transport, ship, and trains, but could also be used in industry, heating in residential and commercial buildings if blended to natural gas in the gas network and provided that issues related to safety and compliance are resolved. Power to hydrogen is envisaged to cope with intermittency of renewables but is not planned to be in place before 2035.

Table 15 - Summary of information for France

CCS is part of the national plan	Yes. 6 $MtCO_2$/y in the industry, around 10 $MtCO_2$/y in energy production from biomass by 2050
Possibility to store in country	Onshore storage
Low capturable volume ($MtCO_2$/y)	17
High capturable volume ($MtCO_2$/y)	43
Interest for Norwegian storage	Industrial actors recognizing the need to store CO_2 in Norway
National support mechanisms in place for CCS	No
CCS deployment timeline	
Government position towards CCS	Recognizing the need but not pushing for it
Public acceptance for CCS	No recent study on the topic
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**High**

Figure 34 summarizes the information found for France regarding the role of CCS / BECCS and hydrogen in their carbon neutrality plan. France is planning to use CCS and BECCS but is not foreseeing a large role for hydrogen from natural gas. No funding mechanism is currently in place to support these projects.

Figure 34: Timeline of deployment of measures envisaged for France in their carbon neutrality scenario involving hydrogen / CCS /BECCS use. *Source: Carbon Limits based on information found in the French national energy and climate plan and inspired from CCC analysis for UK*



Source: Carbon Limits based on information found in the French national energy and climate plan and inspired from CCC analysis for UK

4.6 Germany

4.6.1 Emissions and CCS potential

Germany emitted 805 $MtCO_2e$ in 2019, representing a decrease of over 10% compared to its 2017 emissions of 894 Mt.[168] In 2019, 246 Mt were emitted from the energy sector and 188 Mt from industry. More than half of all emissions came from these sectors. Large CO_2 emitters represented 339 Mt. Within the Paris Agreement, the German 2030 target was set at a level 55% below 1990 emissions, corresponding to total emissions of 543–562 $MtCO_2e$.[169] The Climate Action Plan 2050[170], published in 2016, confirms these targets and further specifies them. It stipulates individual sector targets of 175–183 Mt in the energy sector and 140–143 Mt in industry in 2030, amounting to 61-62% and 49-51% emission reductions compared to 1990 levels, respectively. The Action Plan also explicitly gives room to “the option of a circular economy in industry” using carbon capture technology. By 2050, emission reductions of up to 95% should be achieved according to the document.

While the Climate Action Plan defines the climate targets, the Climate Action Programme[171], introduced in November 2019, outlines tangible measures to achieve them. A main novelty includes the introduction of a national emission trading system for fuel use in the transport and buildings sectors. After a revision, the government agreed to increase the price range it had initially established for the scheme.[172] In the period 2021–2025 emissions will be sold at a set price of 25 EUR/tCO_2 in 2021, 30 EUR/t in 2022, 35 EUR/t in 2023, 45 EUR/t in 2024 and 55 EUR/t in 2025. From 2026 the price will be determined by auctioning. While the price will be limited within a range of 55–65 EUR/t that year, free price formation will apply from 2027 onwards.[173] Simultaneously, the renewable energy levy is to be reduced from 2021 onwards. To further enable the country to reach its climate ambitions, barriers to renewable energy expansion such as the onshore wind turbine distancing rules were eased and the 52 GW PV capacity cap was lifted.

Germany has 183 large facilities in the sectors identified in chapter 2 as medium to high likelihood of CCS, i.e. cement, waste-to-energy, refining, iron and steel and chemicals/petrochemicals. The calculated capturable quantity ranges from 37-89 MtCO2/y. The high potential represents 11% of total German GHG emissions, based on 2017 values.

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[168] Federal Environmental Agency (Umweltbundesamt, 25. March 2020). Indicator: Greenhouse gas emissions. Retrieved from: https://www.umweltbundesamt.de/en/indicator-greenhouse-gas-emissions

[169] Federal Environmental Agency (2020). Treibhausgasminderungsziele Deutschlands. Retrieved from https://www.umweltbundesamt.de/daten/klima/treibhausgasminderungsziele-deutschlands

[170] Federal Ministry for the Environment (2016). Climate Action Plan 2050 – Germany’s long-term emission development strategy

[171] German government (2019). Eckpunkte für das Klimaschutzprogramm 2030. Retrieved from: https://www.bundesregierung.de/resource/blob/997532/1673502/768b67ba939c098c994b71c0b7d6e636/2019-09-20-klimaschutzprogramm-data.pdf?download=1

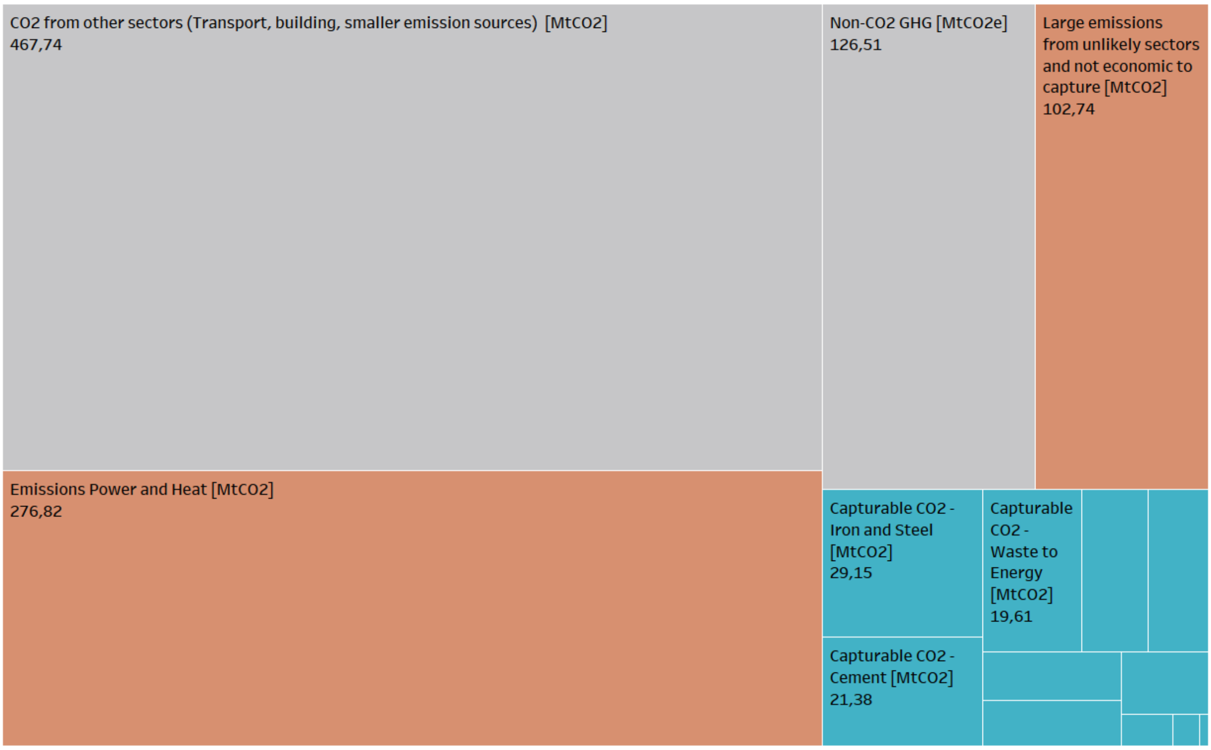
[172] German government (2020). Grundlage für CO_2-Preis steht. Retrieved from: https://www.bundesregierung.de/breg-de/themen/klimaschutz/nationaler-emissionshandel-1684508

[173] German emission trading office (DEHSt, 2020). Nationales Emissionshandelssystem – Hintergrundpapier. Retrieved from https://www.dehst.de/SharedDocs/downloads/DE/nehs/nehs-hintergrundpapier.pdf;jsessionid=4D4BB9E0161C85AE51F95F65EC4109EB.2_cid292?__blob=publicationFile&v=3

Figure 35: Overview of GHG emissions and CCS Potential - 2017 Data – Germany

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.



Source: E-PRTR / Eurostat

Germany possesses a storage potential of 9.1 Gt onshore and 2.9 Gt located offshore in the North Sea according to the Federal Institute for Geosciences and Natural Resources (BGR).[174]

4.6.2 Plans and Policies

CCS / BECCS

After the adoption of the EU CCS directive in 2009, public opposition to CO_2 storage led to regional governments calling for limitations on storage projects. The German CCS Act, introduced in 2012, took those requests into account and halted all CCS projects except for testing and demonstration pilots. The government set a deadline until 2016 for applications for such demonstration projects. The date passed without a single submission. Under the current legal framework, it is thus not possible to set up a CO_2 storage project in Germany. Due to public acceptance issues, tapping the German onshore CO_2 storage potential is thus most likely not politically feasible.

However, the role of CCS in the future decarbonisation of the German economy became a point of discussion again after Chancellor Merkel stated in 2019 that CCS was necessary to achieve the ambitious climate targets.

[174] Acatech (2018). CCU und CCS – Bausteine für den Klimaschutz in der Industrie: Analyse, Handlungsoptionen und Empfehlungen. Herbert Utz Verlag.

In its Climate Action Programme, the German government notes that the majority of climate studies and scenarios confirm that CCS is “indispensable” for achieving net-zero emissions by 2050.[175] The document names German initiatives supporting CCS and CCU but fails to substantiate a German commitment to a rapid uptake of the technology. It lists three measures: firstly, the expansion of the EU’s NER300 programme as part of the EU Innovation Fund from 2021-2030, secondly, the National Decarbonisation programme, a dedicated RD&E funding programme to test industrial-scale deployment of promising technologies that can ensure decarbonisation, and lastly, a programme for the prevention of CO_2 emissions and use of CO_2 in the raw material industry as part of the European industrial strategy. The cost competitiveness of CCS technology in the process industry is highlighted as well as the negative emission potential of BECCS. The document refers to the call of industry representatives for the advancement of CCS technology to ensure its availability by 2030. This is envisaged with explicit consideration of North Sea offshore storage options, CO_2 networks and transportation. A forthcoming government report on CCS is expected to discuss these provisions in more detail while a dialogue with relevant stakeholders should help clarify the relevance of different carbon abatement technologies in the industry sector and their acceptability.[175] More detailed information on research budgets and deployment targets is missing.

In its NECP, Germany also exhibits its funding for its national “CO_2-Win” and “CO_2-Plus” programs as well as the participation in the ERA-net EU project to research among others the future application of CCU technologies.[176]

Furthermore, the industry strategy 2030 sets the target of bringing CCS/CCU technologies to market readiness to reduce CO_2 abatement costs.[177] It also outlines the need for cooperation with Norway, the Netherlands and the UK for the development of CO_2 storage solutions.

An influential study commissioned by the German Industry Association (BDI) concluded emission reductions beyond 80% was not achievable without CCS in the industry sector. However, the German environmental agency (UBA) later published five net-zero scenarios that they hold as feasible without the need for nuclear generation or CCS.[178,179] UBA excluded CCS from its scenarios due to “yet non-manageable environmental risks”, with reference to a 2015 study.[180]

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[175] German government (2019). Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050. Retrieved from: https://www.bundesregierung.de/resource/blob/975226/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019-10-09-klima-massnahmen-data.pdf?download=1

[176] BMWi (2020). Integrierter Nationaler Energie- und Klimaplan. Retrieved from: https://www.bmwi.de/Redaktion/DE/Downloads/I/integrierter-nationaler-energie-klimaplan.pdf?__blob=publicationFile&v=6

[177] BMWi (2019). Industriestrategie 2030. Leitlinien für eine deutsche und europäische Industriepolitik. Retrieved from: https://www.bmwi.de/Redaktion/DE/Publikationen/Industrie/industriestrategie-2030.pdf?__blob=publicationFile&v=10

[178] Prognos & BCG (2018). Klimapfade für Deutschland. (Commissioned by BDI)

[179] UBA (2019). Resource-efficient pathways towards greenhouse gas neutrality – RESCUE. Retrieved from: https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_kurzfassung_eng.pdf

[180] UBA (2015). Stellungnahme des UBA: Landesgesetz zum Kohlendioxid-Speicherungsgesetz erarbeiten. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/stellungnahme_des_umweltbundesamtes_landesgesetz_zum_kohlendioxid-speicherungsgesetz_erarbeiten.pdf

Hydrogen

On the 10th of June 2020, the German government released its hydrogen strategy.[181] The focus is on providing clean hydrogen for the industry and transport sectors under the stipulation that "only hydrogen produced on the basis of renewable energies ("green" hydrogen) is sustainable in the long term". The strategy does not mention the production of "blue hydrogen" in Germany. However, it acknowledges the emergence of a global and European hydrogen market where CO_2-neutral forms of hydrogen will be traded, and states that they will also play a role in Germany on a transitional basis. It is not likely that Germany will be able to produce the quantities of green hydrogen needed from national renewable sources and it is therefore expected to remain an importer of CO_2-neutral hydrogen. Thus, the strategy also recognises the need for collaboration, especially in the North and Baltic seas and with Southern Europe as well as outside the EU (e.g. Morocco), to provide sufficient quantities of clean hydrogen. The strategy document states that focus should lie on the production of hydrogen using offshore wind.[181]

After a long-drawn political debate about the targets, 5 GW of electrolyser capacity, including the necessary offshore and onshore energy generation, were set as the objective by 2030, with another 5 GW to be commissioned preferably by 2035 but by 2040 at the latest. With hydrogen demand of 90-110 TWh (current hydrogen use: 55 TWh) expected in 2030, domestic green hydrogen production is expected to cover only 14 TWh, using up to 20 TWh of renewable energy generation. The strategy explicitly asserts that the electricity demand for H_2 production should not result in an increase in CO_2 emissions. [181]

In the transport sector, hydrogen and derivative power fuels are presented as a low-carbon alternative where direct electrification is not seen as practical or technically feasible. This encompasses heavy transport, not yet electrified trains, maritime transport and aviation.

The action plan divides the strategy in two phases: a market ramp-up by 2023, and the consolidation of the home market as well as the establishment of EU and international cooperation from 2024 onwards.

In total, EUR 7 billion are earmarked for bringing the hydrogen technologies to market and EUR 2 billion are set aside for international partnerships. These funds are provided by the German Covid-19 stimulus package and come in addition to EUR 1.4 billion set aside in the national H_2 R&D programme for 2016-26, the EUR 310 million basic research funding for hydrogen technologies from 2020-23, the EUR 200 million for application-related energy research for hydrogen from 2020-23, the EUR 600 million for the project "Reallabore der Energiewende" (not exclusively hydrogen-related), and EUR 1 billion for the national decarbonisation programme focusing on industrial facilities using hydrogen for manufacturing processes from 2020-23.

Participation in EU Projects of Common Interest, the rapid implementation of the European Green Deal hydrogen initiative, a 2% quota for renewable kerosene in the aviation sector by 2030, reliable proofs of origin for hydrogen and power fuels, the exemption of green hydrogen production from the renewable energy levy, the creation of a market for climate-friendly steel, as well as a CfD pilot for

[181] BMU. (2020). Nationale Wasserstoffstrategie. Retrieved from: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Energieeffizienz/nationale_wasserstoffstrategie_bf.pdf

hydrogen used to abate industrial process emissions, all form part of the policy for kickstarting the emergence of the German hydrogen sector.[182, 183]

Germany wants to use its EU presidency in the 2nd half of 2020 to promote the role of hydrogen, e.g. for the use in sector coupling. In addition, the geopolitical and developmental aspect in future hydrogen trade has been mentioned as an area of priority. Germany recognises the renewable energy potential especially of African countries that could be used to produce and export hydrogen to the EU. A cooperation with Morocco has been initiated that will receive EUR 300 million to build a P2G facility for hydrogen export. The target is to establish hydrogen trade with well-suited countries without negatively affecting their local energy markets or ability to achieve their own energy transition targets. Another project that shows the German leadership ambition is the wish to set up an international hydrogen alliance linked to global climate targets and in close accord with the EU's own initiatives. The idea is to position Germany as an important market for hydrogen use and meet its demand for zero emission energy carriers.

4.6.3 Summary of the information found for Germany

The role of CCS is controversial in Germany. Public opposition, primarily to storage, led to the CCS act of 2012 forbidding onshore storage of CCS. Only last year, the debate around the benefits of CCS for achieving net-zero emissions by 2050 flared up again. Passages in the German NECP show that some commitment to R&D funding for CCS exists but neither are projects planned nor specific targets set. Although the clear focus of the recently published Hydrogen Strategy is on green hydrogen production in- and outside of Germany, there are no provisions against the import and use of blue hydrogen. Since hydrogen production based on domestic renewable energy sources will likely be able to cover only a minor share of expected demand, Germany will have to rely on imports to cover its rising demand for clean hydrogen.

The overall significance of CCS in the country was considered as low given the limited interest on the political side and the strong public opposition. On the other hand, considering the high level of industry emissions in the country, it is likely that CCS will be needed on some sectors and if so, then storage outside of the country seems to be a likely possibility and Norway is a likely candidate.

[182] BMU. (2020). Nationale Wasserstoffstrategie. Retrieved from: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Energieeffizienz/nationale_wasserstoffstrategie_bf.pdf

[183] BMF. (2020). Corona-Folgen bekämpfen, Wohlstand sichern, Zukunftsfähigkeit stärken. Retrieved from: https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Schlaglichter/Konjunkturpaket/2020-06-03-eckpunktepapier.pdf?__blob=publicationFile&v=8

Table 16 - Summary of information for Germany

CCS is part of the national plan	Only R&D projects, no pilots or large-scale projects planned
Possibility to store in country	No storage allowed on land. Some offshore storage potential.
Low capturable volume ($MtCO_2/y$)	37
High capturable volume ($MtCO_2/y$)	90
Interest for Norwegian storage	Due to opposition to local CO_2 storage, offshore storage in Norway might be needed if CCS is pursued (cf. German Industry Strategy[184])
National support mechanisms in place for CCS	No, only R&D funding on a comparatively low level
CCS deployment timeline	No timeline but hope for market readiness by 2030 stated in Industry Strategy
Government position towards CCS	CCS not really considered for the moment
Public acceptance for CCS	Very low public acceptance for storage, different with capture but has not been debated recently
Overall significance of CCS	**Low**
Overall relevance for Norwegian storage	**Medium**

[184] BMWi (2019). Industriestrategie 2030. Leitlinien für eine deutsche und europäische Industriepolitik. Retrieved from: https://www.bmwi.de/Redaktion/DE/Publikationen/Industrie/industriestrategie-2030.pdf?__blob=publicationFile&v=10

4.7 Ireland

4.7.1 Emissions and CCS potential

In Ireland, large emission sources were responsible for 15.6 $MtCO_2$ in 2017. Cumulatively, by 2030, their target is to not exceed 378 $MtCO_2$, while a business-as-usual scenario suggest emissions over the period 2020-2030 to be 480 $MtCO_2$. This means that Ireland would miss its target by 100 $MtCO_2$ under a business as usual scenario, or about 10 $MtCO_2$ annually. Their aim for 2050 is to be at net-zero.[185]

Ireland has four cement plants, one refinery and one waste-to-energy plant, with a total of 2.9 $MtCO_2$/y of capturable emissions.

Figure 36: Overview of GHG emissions and CCS Potential - 2017 Data – Ireland

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

The capture potential represents 5% of the Irish GHG emissions based on 2017 values. Capture on gas fired power plants is also a focus of Ireland and a specificity of the country linked to the fact that it is an island which makes it more difficult to implement electricity trade with other countries. The potential then rises to 20% of the Irish GHG emissions based on 2017 values (12 $MtCO_2$/y).

[185] Government of Ireland, *Climate action plan – annex of actions,* 2019

Ireland has potential CO_2 storage in the Kinsale gas field of about 330 $MtCO_2$.[186] There are also a number of small closed structures in the Central Irish Sea Basin and the Celtic Sea which could be suitable for CO_2 and having, respectively, a potential capacity of up to 50 $MtCO_2$ and 24 $MtCO_2$.[187]

4.7.2 Plans and Policies

CCS / BECCS

Ervia, the national gas and water company, has already identified a CCS project in the southern region of the country, near Cork. Storage in the depleted Kinsale gas field should become available in the late 2020s. In the meantime, they have indicated a strong interest for storage on the Norwegian continental shelf and are being considered as phase I partners of the Northern Lights project.

In its national energy and climate plan, Ireland has no detailed targets for the deployment of CCS, and they consider CCS as part of potential climate mitigation measures. Ireland mentions the "Establishment of a steering group to examine and oversee the feasibility of the utilisation of CCS in Ireland" as a measure to be put in place before the end of 2020. This includes agreeing on research investment by Ervia/Gas Networks Ireland in CCS feasibility, monitoring the progress of Ervia proposal in Cork and drafting necessary legislation and regulatory regime if the CCS research is positive.[188]

Bioenergy is presented as a cost-effective renewable energy substitute in Ireland's Climate action plan. Sustainable biomass can be covered by grants from the SEAI (Sustainable Energy Authority of Ireland)[189]. The combination of biomass and CCS is, however, not mentioned in the plan.

So far, the public opinion in Ireland has not been negative towards CCS and no opposition has been brought to light. Authorities recognize the necessity of CCS in order to reach Ireland's decarbonization targets.[190]

Hydrogen

Hydrogen, and more specifically hydrogen vehicles, is mentioned only once in the NECP as one of the multiple options for climate change mitigation, which requires further assessment, alongside biomethane and anaerobic digestion substitutes for natural gas. Hydrogen is not part of the list of actions published in the Climate action plan.

[186] SEI and EPA, Assessment of the potential for geological storage of CO_2 for the Island of Ireland, September 2008

[187]Geological Survey Ireland, *Carbon capture and storage*, https://www.gsi.ie/en-ie/programmes-and-projects/geoenergy/activities/Pages/Carbon-Capture-and-Storage.aspx

[188] Government of Ireland, *Climate action plan – annex of actions,* 2019

[189] SEAI website, https://www.seai.ie/

[190] Interview with Ervia

Table 17 - Summary of information for Ireland

CCS is part of the national plan	Yes
Possibility to store in country	Offshore storage
Low capturable volume ($MtCO_2/y$)	3
High capturable volume ($MtCO_2/y$)	3
Interest for Norwegian storage	To deploy CCS faster in Ireland, before storage becomes available more locally
National support mechanisms in place for CCS	
CCS deployment timeline	2028-2030
Government position towards CCS	Are favourable to CCS, have the intention of supporting it through legislation and are monitoring existing projects
Public acceptance for CCS	Not negative
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**Medium**

4.8 Netherlands

4.8.1 Emissions and CCS potential

In 2017, the Netherlands emitted 205 $MtCO_2e$, of which 90 were emitted by large emitters. The Netherlands target for 2030 is to reduce emissions by 49% compared to 1990 and 95% by 2050.[191]

There are 35 Dutch facilities which are in the sectors of medium and high likelihood for CCS, as identified in chapter 2. These facilities, primarily chemicals/petrochemicals, refining, waste-to-energy, and iron and steel have capturable emissions of about 24 $MtCO_2$/y. The capture potential represents about 15% of the Dutch emissions in 2017.

Figure 37: Overview of GHG emissions and CCS Potential - 2017 Data – Netherlands

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

Source: E-PRTR / Eurostat

The Netherlands has both large onshore and offshore potential CO_2 storage areas, mainly in depleted gas fields. The capacity is estimated around 1,400 Mt offshore, of which 600 Mt should be available by 2028, and 900 Mt onshore. Before unlocking this potential, regulatory changes on the transfer of ownership and decommissioning of gas field after they have been depleted, are necessary. These regulatory aspects have been identified as potential barriers to the development of CCS projects in the

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[191] Dutch government, *National Energy and Climate Plan,* 2019

Netherlands. The Netherlands also has a dense network of natural gas transmission pipelines which could potentially be reused to transport CO_2. [192]

4.8.2 Plans and Policies

CCS / BECCS

CCS is considered as "an inevitable transition technology for reducing CO_2 emissions in sectors where no cost-effective alternative is available in the short term".[193] The Netherlands has also expressed interest in working with other Member States for the joint development of CCU/CCS and green hydrogen, according to the NECP.

Initially, the Netherlands had planned to capture and store 18 $MtCO_2$/y by 2030, but recently they have reviewed this target down to 7.2 $MtCO_2$/y in agreement with industries and NGOs, as few believed the initial goal to be realistically achievable.[194]

The Dutch government has put in place a support scheme called SDE++, which was initially aimed at renewable energy, but that now also includes CCS, available until 2035 to CCS projects. The subsidy can provide up to bn EUR 4 billion over a period of 15 years. The grants are, however, limited to techniques, processes and sectors without a cost-effective alternative. There is also a limit of 7.2 $MtCO_2$/y for subsidising industrial CCS. Once the target is reached, new projects will no longer be considered for new subsidies from the Dutch government. Existing projects will, however, continue to receive their subsidies for the entire 15-year cycle for which they have applied. [195]

Currently, several projects in the Netherlands are planning to rely on such funding, as well as on European funding, such as the Porthos project in Rotterdam and the Athos project in Amsterdam.

It is highly unlikely that the entire funding will go to CCS projects as the grant is also meant for renewable energy projects and because the public acceptance to financing CCS to such a large extent. [195]

In 2019, the Dutch government decided, on top of the ETS system, to implement a carbon tax. It is currently still under discussion but could provide additional incentive for large emitters to implement CCS.[196]

The costs in the Netherlands for carbon capture, all sectors combined, have been estimated around 40-50 EUR/tCO_2 for pre-combustion and 100 EUR/t for post-combustion. [197]

BECCS is not mentioned specifically in the Integrated National Energy and Climate plan.

Hydrogen

In their National Energy and Climate Plan, the Netherlands emphasize the importance of blue and green hydrogen in order to reduce their emissions. They intend to develop a hydrogen programme

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[192] CE Delft, *Feasibility study into blue hydrogen – technical, economic and sustainability analysis,* July 2018

[193] *Integrated National Energy and Climate plan 2021-2030,* November 2019

[194] CE Delft, *Feasibility study into blue hydrogen – technical, economic and sustainability analysis,* July 2018

[195] Interview with Porthos

[196] NOS, *CO_2-heffing kost industrie voorlopig wienig,* May 2020, https://nos.nl/nieuwsuur/artikel/2335103-co2-heffing-kost-industrie-voorlopig-weinig.html

[197] CE Delft, *Feasibility study into blue hydrogen – technical, economic and sustainability analysis,* July 2018

which will focus on “unlocking the supply of green hydrogen, developing the necessary infrastructure and cooperating with various sector programmes, and facilitating ongoing initiatives and projects”. [198]

Costs are expected to decrease, as the number of projects and production capacity increases, from 100 million EUR/100 MW today to 35 million EUR/100 MW by 2030. The government plans to support demonstration facilities and pilots with up to 30-40 million EUR/y. This money will be taken from the climate envelope, using, where possible, existing schemes and funding options. [199]

Table 18 - Summary of information for the Netherlands

CCS is part of the national plan	Yes (7.2 $MtCO_2$/y by 2030)
Possibility to store in country	Onshore and offshore storage
Low capturable volume ($MtCO_2$/y)	9
High capturable volume ($MtCO_2$/y)	24
Interest for Norwegian storage	Have access to significant storage capacity, but timeliness and legislations could make storing in the Netherlands uncertain
National support mechanisms in place for CCS	Yes, up to EUR 4 billion over 15 years through SDE++ subsidies
CCS deployment timeline	By 2030
Government position towards CCS	Are favourable to CCS, have the intention of supporting it financially
Public acceptance for CCS	No recent study on the topic
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**Low**

198 *Integrated National Energy and Climate plan 2021-2030,* November 2019

199 *Integrated National Energy and Climate plan 2021-2030,* November 2019

4.9 Sweden

4.9.1 Emissions and CCS potential

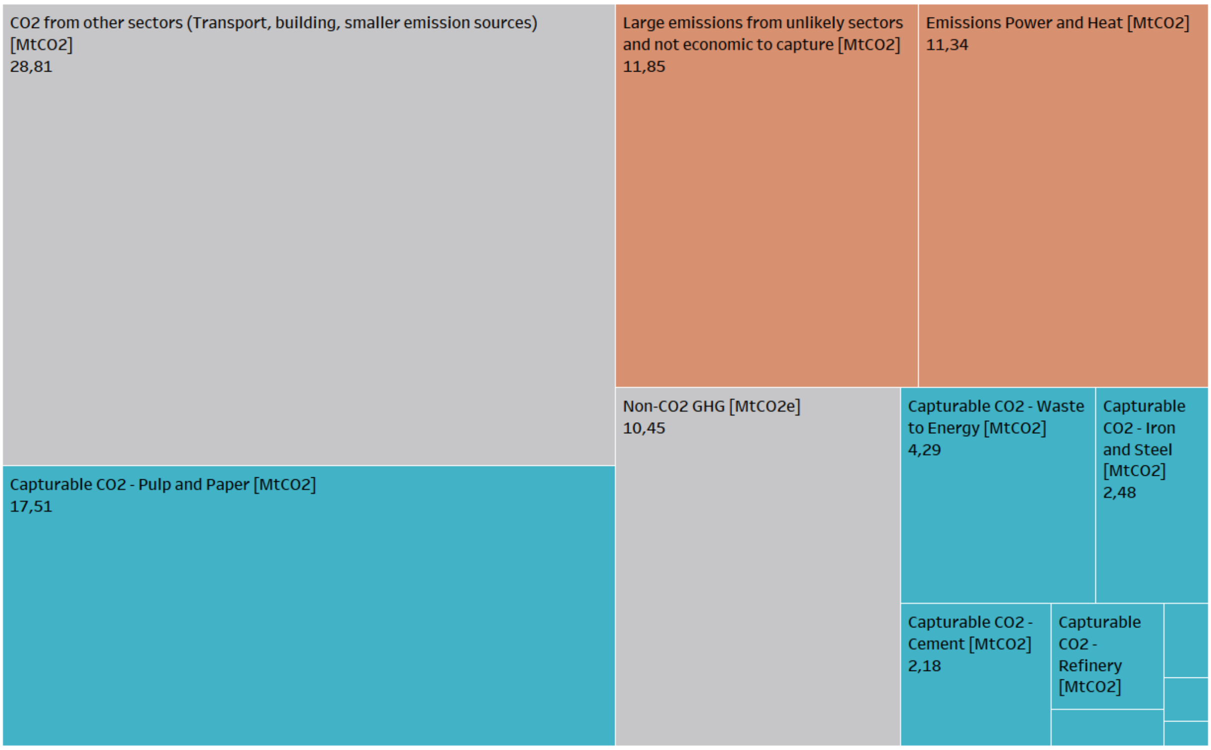
Sweden had total emissions of 55.5 $MtCO_2e$ in 2017. CO_2 emissions from large sources totalled 17.1 Mt in 2017. In addition, large sources emitted 34 Mt of CO_2 from combustion of biomass. Sweden has 32 large facilities in the iron and steel, waste-to-energy, refining, cement, and chemicals sectors, with capturable emissions of 11 MtCO2/y. With about 60 facilities combusting biomass in the electricity and heat production and pulp and paper, the capturable emissions increase to about 39 $MtCO_2$/y. The industry capture potential represents about 20% of the Swedish GHG emissions in 2017, increasing to 70% when including power and heat, pulp and paper.

According to its NECP, Sweden's long-term emission target is to reduce its net emissions of greenhouse gases to zero by 2045. Sweden also has intermediate targets of 63% reductions by 2030 and 75% by 2040, however, they encompass only the ESR (Effort Sharing Regulation) sectors and not the EU ETS sectors. The 2050 net-zero target means that greenhouse gases from Swedish territory must be at least 85% lower in 2045 than they were in 1990. At the 85 % level, the greenhouse gas emissions that remain are mainly methane and nitrous oxide, and these can be compensated for through "additional measures", such as carbon storage in forestry or BECCS.

Figure 38: Overview of GHG emissions and CCS Potential - 2017 Data – Sweden

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.



Source: E-PRTR / Eurostat

The Swedish official report on a strategy for negative greenhouse gas emissions considered storage from Swedish CCS. While the report specified that it is likely that there is domestic storage in Sweden, knowledge about their capacities was deemed to be poor. The strategy concluded that Sweden should not prioritize establishing a storage site, but rather depend on sea transport to storage outside Sweden, for example Norway or another North Sea country.

4.9.2 Plans and policies

CCS/BECCS

While the national energy and climate plan has no specific target on CCS, there is an emphasis on contribution from CCS both on fossil sources and on bio-CCS to achieve negative emissions. According to the national energy and climate plan, capture and storage of carbon dioxide of fossil origin must be included in the measures to achieve the 2050 target in the absence of reasonable alternatives. The “additional measures”, which could offset a maximum of 8% in 2030 and 15% in 2045, could include net removal by forests and land, verified emission reductions through investments in other countries and capture and storage of biogenic carbon dioxide (BECCS). No specific targets have been set for CCS in the NECP.

After 2045, the Swedish target is to achieve negative emissions. To achieve this, the additional measures must be taken into use. In the Swedish official report on a strategy for negative greenhouse gas emissions, the additional measures for this were assessed. A guiding principle for the strategy was spreading the risks across multiple measures. There is a risk that some initiatives may fail to deliver negative emissions, i.e. that the market for trading verified emission reductions internationally might fail or that geological storage sites for Swedish CO_2 would not become accessible. BECCS was identified as an important additional measure to achieve negative emissions. Sweden’s high share of biomass production and usage, primarily in energy and industry, allow for a significant use of BECCS. Due to the long lead times, the strategy stated that if BECCS is to play a significant role in climate policy in 2045, the first plants need to be in operation before 2030. The strategy therefore calls for immediate action from the Swedish state. The volume of additional measures was proposed to be built up in line with the proposed targets for 2030 (3.7 $MtCO_2e$ total, whereof 1.8 $MtCO_2$ from bio-CCS) and 2045 (10.7 $MtCO_2e$ total, whereof 3-10 $MtCO_2$ from bio-CCS). The costs of bio-CCS were estimated to be in the range of SEK 400 to 600 for capture in pulp and paper industry and CHP production. Transportation and storage were estimated to cost between 250 and 500 SEK/tonne of CO_2.

Policy measures such as investment support are in place, though currently not identified to be sufficient for realisation of full-scale projects. The Swedish government has recently decided to ratify the amendment to the London protocol. This was mentioned as a necessary action in the national energy and climate plan to allow for the development of CCS in the country.[200]

The Swedish state has in place some financing mechanisms for CCS-related projects, through the Swedish Energy Agency. In the NECP, the planned CCS project at the Preem Refinery in Lysekil was mentioned, with preliminary studies being financed with SEK 7.7 million and co-financed by Gassnova with NOK 9.5 million.

In 2019, the Swedish government allocated SEK 100 million to pilot projects aimed at accelerating the deployment of CCS and BECCS.[201] Through the Industriklivet initiative, support is towards research and innovation projects which contribute to negative emissions, for example bio-CCS. The support is planned to be at SEK 100 million annually until 2020, thereafter SEK 50 million annually until 2027. [202]

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[200] Regeringskansilet, *Sverige godkänner regler som möjliggör export av koldioxid avsedd för lagring under havsbotten*, June 2020, https://www.regeringen.se/pressmeddelanden/2020/06/sverige-godkanner-regler-som-mojliggor-export-av-koldioxid-avsedd-for-lagring-under-havsbotten/

[201] https://www.di.se/hallbart-naringsliv/100-miljoner-till-ccs-i-varandringsbudgeten/

[202] http://www.energimyndigheten.se/utlysningar/industriklivet-negativa-utslapp-forskning-och-innovation/

The strategy recommended that the Government should task the Swedish Energy Agency to put in place a support mechanism for full-scale bio-CCS using reverse auctioning, initially limited to building up a capacity of 2 $MtCO_2$/y.

Hydrogen

In the national energy and climate plan, the Preem CCS project was mentioned. The project plans CCS on the refinery in Lysekil has the goal of capturing CO_2 from the hydrogen production unit, with operations from 2025.

The Energyklivet initiative has also supported HYBRIT, a research project towards fossil free iron and steel. A combination of hydrogen direct reduction of iron and electric arc furnaces is studied in the project. The goal is to have fossil-free steel production by 2035. The pilot phase will last until 2024, with a subsequent demonstration plant phase from 2025-2035. The project plans to use electricity to produce green hydrogen and for the electric arc furnaces, increasing the electricity consumption around 15 TWh.[203]

Table 19 - Summary of information for Sweden

CCS is part of the national plan	Yes
Possibility to store in country	No
Low capturable volume ($MtCO_2$/y)	7
High capturable volume ($MtCO_2$/y)	11 (39 including power/heat and paper/pulp)
Interest for Norwegian storage	Swedish official report mentions explicitly Norway
National support mechanisms in place for CCS	Energiklivet initiative, support of SEK 100 mill. towards negative emissions, including bio-CCS
CCS deployment timeline	
Government position towards CCS	Are favourable to CCS, have the intention of supporting it financially
Public acceptance for CCS	No recent study on the topic
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**High**

[203] http://www.hybritdevelopment.com/

4.10 United Kingdom

4.10.1 Emissions and CCS potential

The United Kingdom (UK) is the second highest emitting country of the region (behind Germany) with 391.5 $MtCO_2e$ in 2017.

UK has not yet submitted its final NECP as of June 2020 and should have as it is still subject to EU law until December 2020[204]. The draft NECP was submitted in January 2019 and in the document, it is highlighted that the UK government requested advice from the Committee on Climate Change (CCC)[205] on the impacts of the Paris Agreement for UK's long-term emissions reduction target and a net-zero target. The advice from the CCC were received in May 2019[206]. This document details the actions and policies needed to reach a net-zero target by 2050 for UK, 2045 for Scotland, and a 95% reduction target for Wales compared to 1990. The Energy and Clean Growth Minister Chris Skidmore signed in June 2019 a legislation to commit the UK to a legally binding target of net-zero emissions by 2050, following the advice from CCC. This plan could require annually up to GBP 50 billion (1-2% of 2050 GDP).

Large emission sources in UK emitted 145 $MtCO_2$ in 2017. The 65 facilities in waste-to-energy, refining, iron and steel, cement and chemicals/petrochemicals sectors have a capture potential of 33 MtCO2/y. The capture potential on industry represents about 9% of the British GHG emissions in 2017. This value is in line with the CCS requirements set out for industry by CCC (24 $MtCO_2$/y). The UK is one of the few countries also considering CCS on power generation, the potential would then increase to 115 $MtCO_2$ as of 2017 (23% of the British GHG emissions in 2017). This is lower than the CCC's Further Ambition scenario value to achieve net-zero emissions (discussed below), which also includes blue hydrogen production.

[204] http://hydrocarbons21.com/articles/9429/six_eu_countries_still_late_with_climate_plans

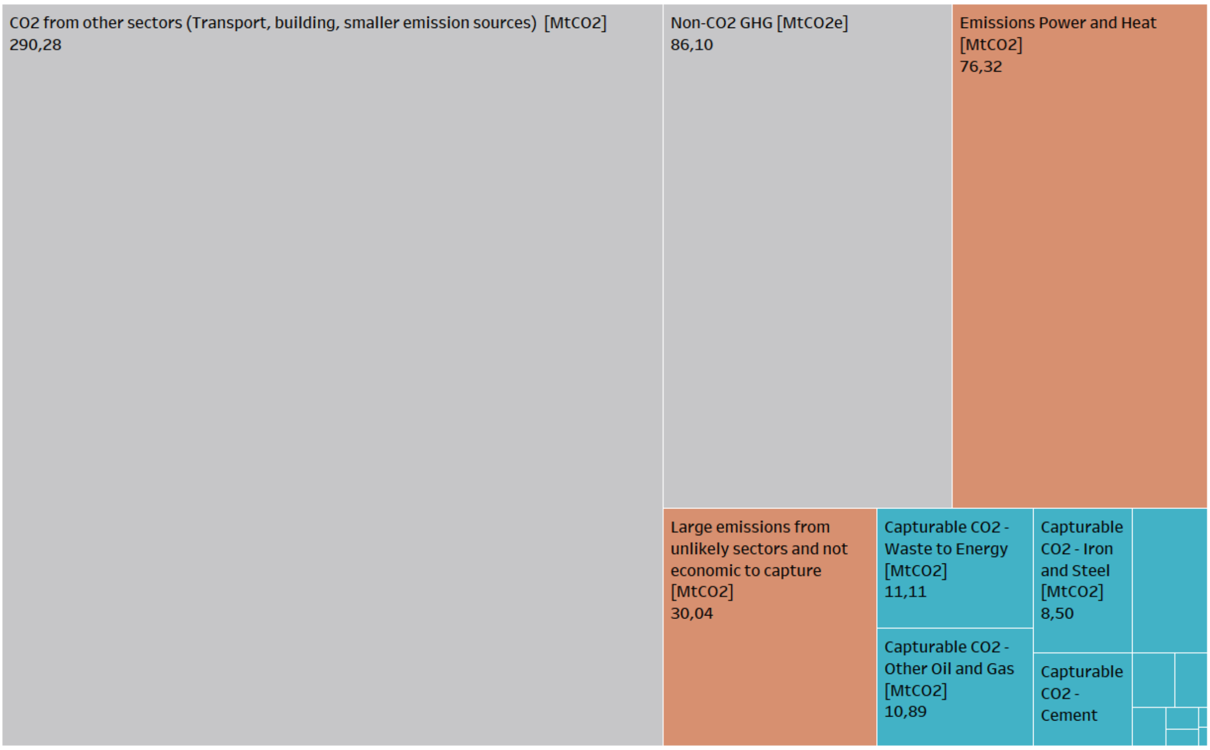
[205] CCC is an independent, statutory body established under the Climate Change Act 2008. Their purpose is to advise the UK and devolved governments on emissions targets and to report to Parliament on progress made in reducing greenhouse gas emissions and preparing for and adapting to the impacts of climate change.

[206] Committee on Climate Change, Net Zero The UK's contribution to stopping global warming, May 2019 https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

Figure 39: Overview of GHG emissions and CCS Potential - 2017 Data – UK

In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO_2 – in orange: remaining emissions

Both fossil and biomass CO_2 are represented on this figure.

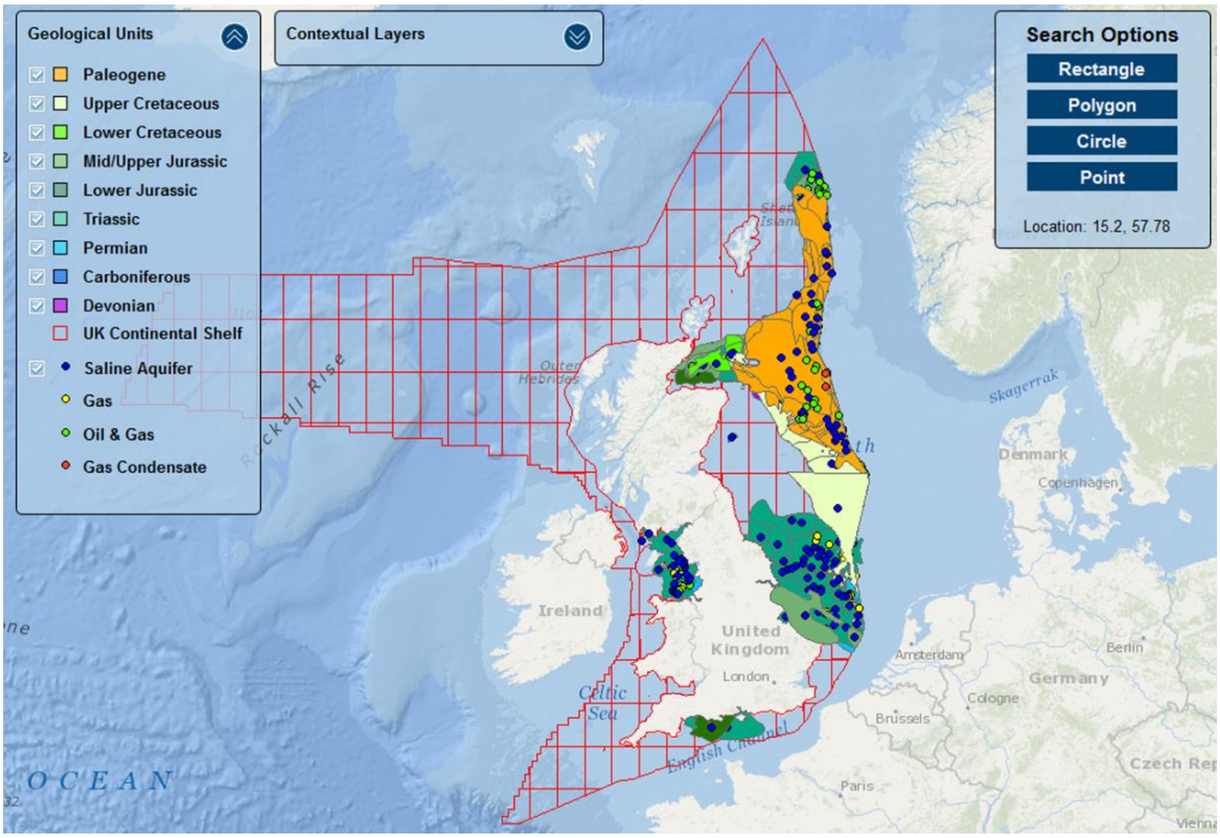


Source: E-PRTR / Eurostat

The UK has some of the highest CO_2 storage capacity in Europe. The storage capacity is estimated to be around 78 $GtCO_2$.[207] The majority of this storage capacity is made up of saline aquifers. A CO_2 storage evaluation database, CO_2 Stored, gives an overview of the location of the storage sites and of their capacities (See Figure 40). It is highly likely that UK will store its CO_2 on its continental shelf rather than on the Norwegian one. However, some projects developed in the UK consider Northern Lights as a back-up option in case their initial planned storage site is not ready on time or is not as promising as expected.

[207] (P50 data) from Bentham et al, CO_2 STORage Evaluation Database (CO2 Stored). The UK's online storage atlas., Energy Procedia 63 (2014) 5103 – 5113

Figure 40: CO_2 storage units around UK



Source: CO_2 Stored[208]

4.10.2 Plans and Policies

CCS / BECCS

CCS is key in the decarbonisation strategy of the UK. CCS on industry, combined with bioenergy, hydrogen and electricity production is seen as a necessity and not an option according to the CCC.

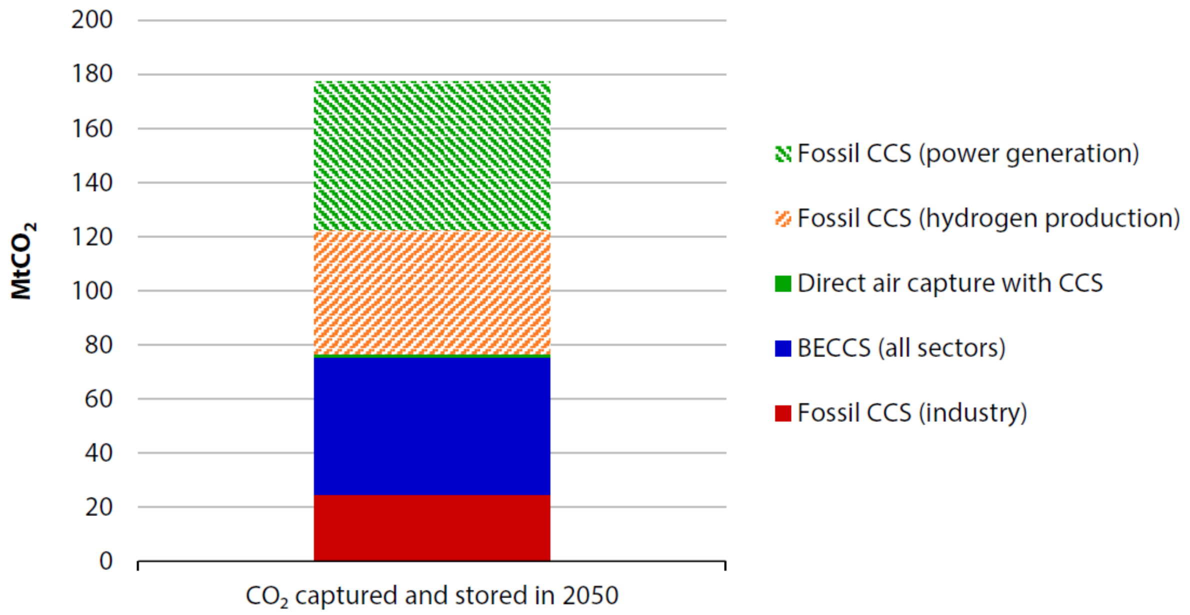
Different scenarios give an annual capture and storage of 75-175 $MtCO_2$ in 2050. CCS in the industry, the application of BECCS in the industry and the power sector and Direct Air Capture with CCS (DACCS) could represent respectively 24, 51, and 1 $MtCO_2$/y of emission reduction by 2050. The rest being necessary on power generation and hydrogen production based on fossil fuels. This would require a major CO_2 transport and storage infrastructure servicing at least five clusters.

The biomass potential in the UK is about 200 TWh. Of this, 173 TWh falls within BECCS in 2050, providing 51 $MtCO_2$ of removals. A small amount of biogas (14 TWh) is assumed to be available after reductions in food waste, of which half is assumed to be used in gas-fired CCS power generation.

The scenarios developed take into account the relative cost effectiveness of the different reduction measures. BECCS on the power sector could cost 125-300 GBP/tCO_2, DACCS 300 GBP/tCO_2, CCS on the power sector 80-120 GBP/$tCO_2$and CCS on industry between 95-120 GBP/tCO_2.

[208] http://www.co2stored.co.uk/home/index

Figure 41: Total CO_2 captured and stored in the Further Ambition scenario developed by CCC - 2019



Source: CCC (2019)

Previous scenarios recommended first two CCS clusters in operation before 2030, to capture at least 10 $MtCO_2$. The first cluster was recommended to start operating by 2026. For a net-zero target the CCC envisages that more will be needed before then, suggesting that at least one of the clusters has substantial production of low-carbon hydrogen. The CCC also urges the Government to take a lead on infrastructure development, with long-term contracts to reward carbon capture plants and encourage investment.

The UK government has already supported the development of several FEED (front end engineering and design) studies for CCS in the UK (e.g. Peterhead, Longannet, etc.) and has put forward under the CCUS Innovation Programme up to GBP 24 million of grant funding to support feasibility studies, industrial research, experimental development projects, infrastructure projects in 2018. Drax, ACORN, HyNet and the Clean Gas project and Tees Valley cluster are among the projects that have received support. On June 12th, ACORN has been set to receive support from the Scottish government for post Covid-19 energy transition to reach Scotland's net-zero targets by 2045 and protect jobs and businesses.

The CCC plans to leverage the Exchequer funding to incentivize industries to reduce their emissions. This will need to be done in ways that do not affect the companies' competitiveness and therefore rely on energy and resource efficiency, electrification, hydrogen and CCS. In the long term, the following mechanisms will be required: international sectoral agreements, procurement, and product standards to require consumers to buy or use low-carbon products or through border-tariff adjustments reflecting carbon content.

Hydrogen

The UK plans to develop a hydrogen economy to supply industrial processes, long-distance HGVs and ships, and for electricity and heating. For heating, by 2035, existing homes should replace their heating systems for it to be low-carbon or ready for hydrogen, so that the share of low-carbon heating increases from 4.5% today to 90% in 2050. New transport infrastructure will be necessary. In the CCC scenario, the UK hydrogen production capacity in 2050 could be comparable to the current UK fleet of gas fired power stations. The hydrogen used in these scenarios is assumed to come mainly from steam methane reforming with CCS in the UK.

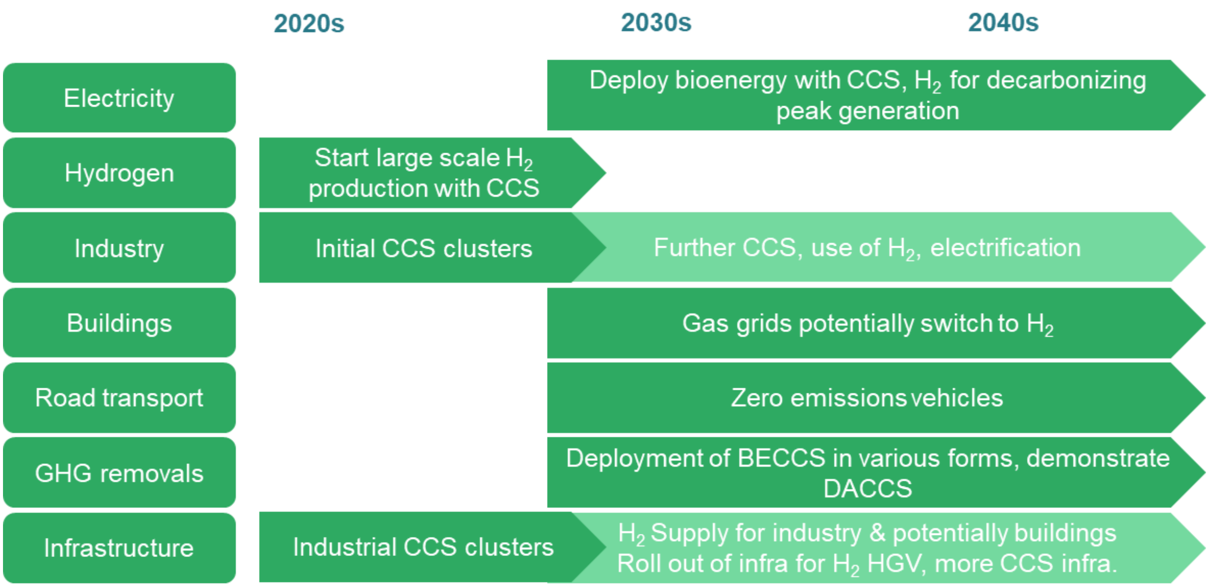
Table 20 - Summary of information for UK

CCS is part of the national plan	Yes (>10 $MtCO_2$/y by 2030, 75-175 $MtCO_2$/y in 2050)
Possibility to store in country	Offshore storage available
Min Capturable volume ($MtCO_2$/y) - 2050	17
Max Capturable volume ($MtCO_2$/y) - 2050	175[209] (34)
Interest for Norwegian storage	Considered as a back-up option for some projects
National support mechanisms in place for CCS	Yes
CCS deployment timeline	From 2024 on
Government position towards CCS	Key for reaching net-zero. Funding made available
Public acceptance for CCS	No recent study on the topic
Overall significance of CCS	**High**
Overall relevance for Norwegian storage	**Low**

Figure 34 summarizes the information found for UK regarding the role of CCS / BECCS and hydrogen in their carbon neutrality plan.

[209] Data from the net-zero plan including CCS on power and heat and BioCCS.

Figure 42: Timeline of deployment of measures envisaged for UK in their carbon neutrality scenario involving hydrogen / CCS /BECCS use.



Source: inspired from CCC analysis for UK

Box 8 - Other countries

Other countries

Other European countries could, in a more distant future, also be interested in carbon storage in the North Sea. For example, Switzerland has studied the possibility to reuse an oil pipeline to Italy to transport carbon to a shipping hub. These have not been reported here as countries of interest because it is unlikely that they will be first movers on CCS projects with storage on the NCS. They should, however, not be disregarded for later phases.

https://www.rts.ch/play/tv/19h30/video/un-projet-suisse-de-reseau-de-pipelines-pour-transporter-le-co2-vers-la-mer-du-nord?id=11362338

4.11 Summary of findings for the selected countries

The review of the selected nine countries indicates that many have recently increased interest for CCS. Seven of the countries appear to recognize the need for CCS to achieve their climate ambitions. In their national energy and climate plans, the countries have varying degrees of precision and detail in the timeline for the deployment of CCS and the volumes that would need to be captured. The countries' main focus is on difficult-to-abate industrial emissions, but there also appears to be an increased interest towards CCS on biogenic CO_2 to achieve negative emissions. The UK and France seem to have the most detailed ambitions on CCS, with targets for 2030 and 2050.

Only a few countries have significant national support mechanisms for CCS planned or in place. Notably, these are the same countries which have high potentials for CO_2 storage offshore, the UK, Netherlands, and Denmark. If this were to remain the case, this means that projects in the other countries would rely heavily on European funding to be able to move forward.

Collectively, the selected countries have capturable CO_2 volumes[210] of about 100 $MtCO_2/y$ (low estimate sectors) up to about 400 $MtCO_2/y$ (high estimate sectors, plus certain additional sectors in Sweden and UK). By comparison, the rest of the EU countries have capturable emissions between 80-160 $MtCO_2/y$ (low estimate and high estimate sectors, respectively).[211]

Limited interest in storage of CO_2 on the Norwegian continental shelf has been identified in countries which have access to sufficient CO_2 storage within their country borders. Three of the selected countries have been assessed as having a high likelihood of sending captured CO_2 to Norway for storage (Belgium, France and Sweden) and three others have a medium likelihood (Denmark, Germany and Ireland). There can be multiple barriers to the development of CCS and two countries have been attributed a low score for the significance of CCS: Germany and Finland. These countries each depict different barriers. In Finland, the limitations come from limited amounts of CO_2 emissions and little apparent interest in CCS. In Germany, it is the public opposition to CCS which could pose a major barrier for the development of CCS projects.

The role given to hydrogen as a measure to achieve climate targets varies strongly between the countries considered. Some countries, such as Finland and Ireland, hardly mention hydrogen in their NECPs. On the other end of the spectrum, the UK sees hydrogen as a key for decarbonisation of large parts of the economy. The countries also differ in their approach to blue and green hydrogen. The Netherlands and the UK see blue hydrogen as very important for decarbonisation, France recognises it as potentially important in the industry, while other countries, such as Germany and Denmark mainly focus on green hydrogen. In Germany this will likely imply large import of hydrogen, as the country has set ambitious targets for hydrogen demand, while only aiming to cover a small share with domestic green hydrogen production.

The following figures show where the countries stand in terms of minimum and maximum capturable emissions depending on the significance of CCS and relevance for Norwegian storage.

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[210] Low capturable quantity: the country's capturable CO_2 emissions from the sectors where CCS is considered to be most important to achieve net-zero emissions, i.e. cement production and waste-to-energy. These two sectors are to reach net-zero emissions without ceasing production, CCS is necessary. High capturable quantity: capturable CO_2 emissions from large iron and steel, chemical/petrochemical, and refinery facilities in each country, in addition to cement and waste-to-energy. For certain countries with explicit interest for CCS on power generation (UK) or BECCS (Sweden), we have also added these capturable emissions.

[211] Future potentials for blue hydrogen production (with the exception of CCS in hydrogen production in refining and chemicals/petrochemicals) are not included in the country level analysis, since it is uncertain where such facilities would be located.

Figure 43 - Low capturable volume per country according to significance of CCS and Relevance for Norwegian storage

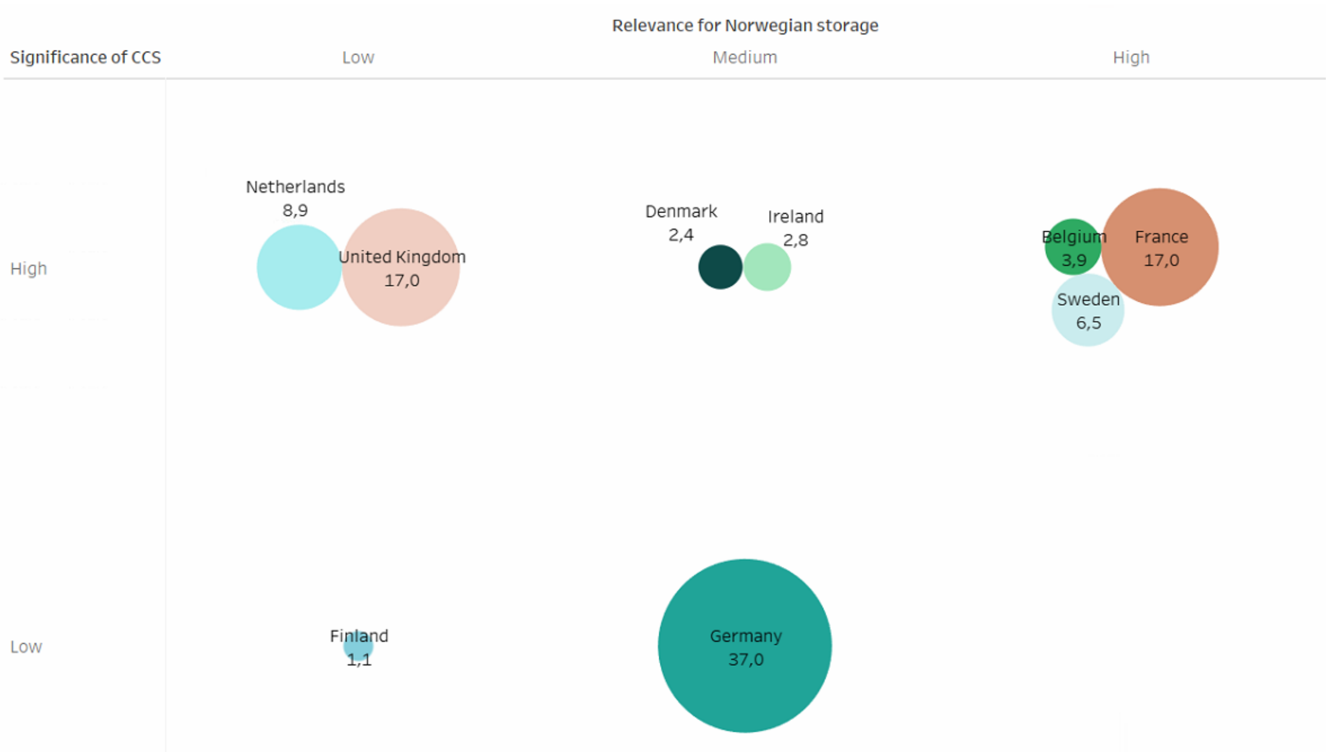
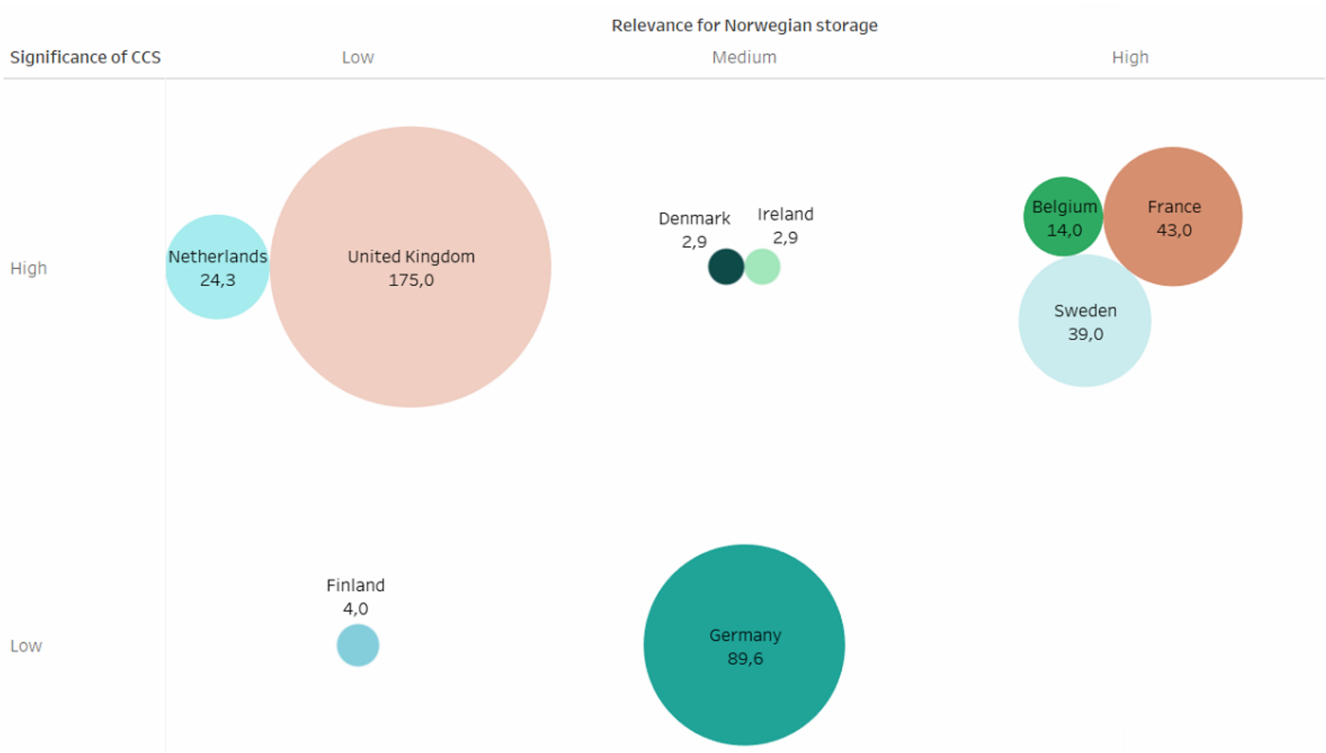


Figure 44 - High capturable volume per country according to significance of CCS and Relevance for Norwegian storage



The following table presents a summary of the potential interest for the Norwegian storage in the selected countries.

Table 21 - Summary assessment of CCS in selected countries

Assessment of CCS in selected countries									
	BE	**DK**	**FI**	**FR**	**DE**	**IR**	**NL**	**SE**	**UK**
CCS is part of the national plan	✓	✗	✗	✓	—	✓	✓	✓	✓
Possibility to store in country	✗	✓	✗	—	✗	✓	✓	✗	✓
Min Capturable volume ($MtCO_2/y$) – 2050	4	2	1	17	37	3	9	7	17
Max Capturable volume ($MtCO_2/y$) – 2050	14	3	4	43	90	3	24	39	175
Interest for Norwegian storage	✓	—	—	✓	✓	✓	—	✓	—
National support mechanisms in place for CCS	✗	✓	✗	✗	✗		✓	—	✓
Overall significance of CCS	✓	✓	✗	✓	✗	✓	✓	✓	✓
Overall relevance for Norwegian storage	✓	—	✗	✓	—	—	✗	✓	✗

✓ The green check marks indicate a favourable situation for CCS (for example: CCS part of the national plan, potential storage in the country, national financial support for CCS)

✗ The red crosses depict a situation which is unfavourable to CCS (for example: no political support for CCS, no storage in the country)

— The orange bars are used when it is unclear whether the situation in the country will be favourable or not for CO_2 storage in Norway (for example: will low public acceptance of CCS in Germany lead to limited capture projects or will it lead to as many capture projects, but all with storage abroad. In which case Norway would be well placed for storing CO_2). It is also used when there are uncertainties (for example: potential CO_2 storage areas have been identified in France, but there is currently no thorough assessment that has been made of their potential capacity).

The cells with no marks represent criteria which have not been assessed due to lack of information on a specific topic in that country.

It is also important to note that this assessment gives a general view for each country. Individual projects will not necessarily follow the trend of the country in which they are set up. For example, 7 companies have signed an MoU with Equinor, some of which are considering capture projects in countries with low interest for CCS (e.g. Arcelor Mittal Bremen in Germany).[212]

More detailed information on each country is available in the corresponding section above.

[212] NS Energy, *Seven European firms to join Equinor's Northern Lights project in Norway,* September 2019, https://www.nsenergybusiness.com/news/equinor-northern-lights-project-mou/

5. Short- and long-term deployment of CCS in EU 28

This section investigates the future deployment of CCS in the EU28 countries. Carbon capture and storage projects require many years[213] of planning, design, and construction before they enter into operation. Hence, many of the projects that can realistically be realised before 2030 are already at the planning stage. Therefore, the assessment of possible deployment is based on a mapping of current project plans, availability of EU and state funding, and timeline for deployment. First, we have gathered information on the projects, assessing their storage opportunities and timelines. We then have estimated the amount of EU funding which could support CCS projects before 2030, and the CCS capacities these could support, based on rough calculations. We then estimate the CCS volumes which could be stored at the Northern Lights project towards 2030.

The investigation of the range of possible CCS volumes towards 2050 is based on the analyses in the previous chapters, with emphasis on the range of policy uncertainties and estimated capturable CO_2 quantities in chapter 2.

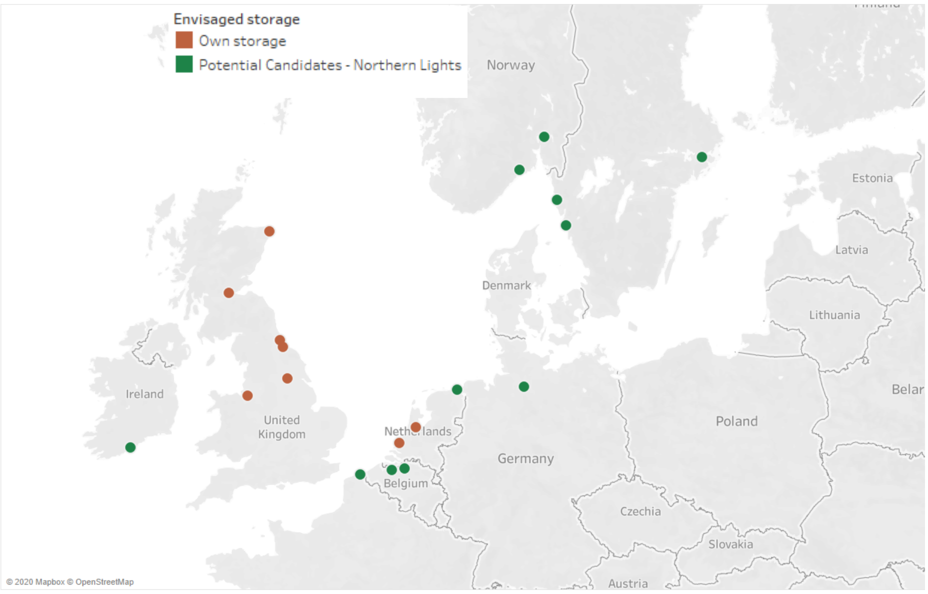
To assess the planned projects, we have collected information from public databases and interviewed industry actors involved in the projects.[214] Some projects have identified their own storage locations, while others are considering Northern Lights as a solution for transport and storage. A total of 41 potential CCS projects have been identified. Eight of these projects (red dots in Figure 45) are planning to develop their own storage, some of which are planned as clustered projects with capture from multiple sources and industries. However, even projects with their own storage locations have indicated that they might require the use of Northern Lights as a back-up solution for the start of operation and in case the identified storage solution is not as promising as expected.

Not including the Norwegian projects, we have identified 11 capture projects which plan to use Northern Lights for transport and storage (green dots on Figure 45). These projects are primarily in countries which do not have storage possibilities in the near term. However, there are projects in countries with storage potential such as the Netherlands and Ireland that still plan to use Northern Lights. In addition, we have identified an additional 22 possible projects currently at earlier stages of planning. Primarily, these are in countries without access to storage options. If realised, these projects could be future prospects for Northern Lights storage.

[213] A review of project timelines indicates seven years from planning begins to start of operations is typical.

[214] Multiple Norwegian CCS projects are also planned but are outside the scope of this report and therefore not included here.

Figure 45: Map of projects in Europe



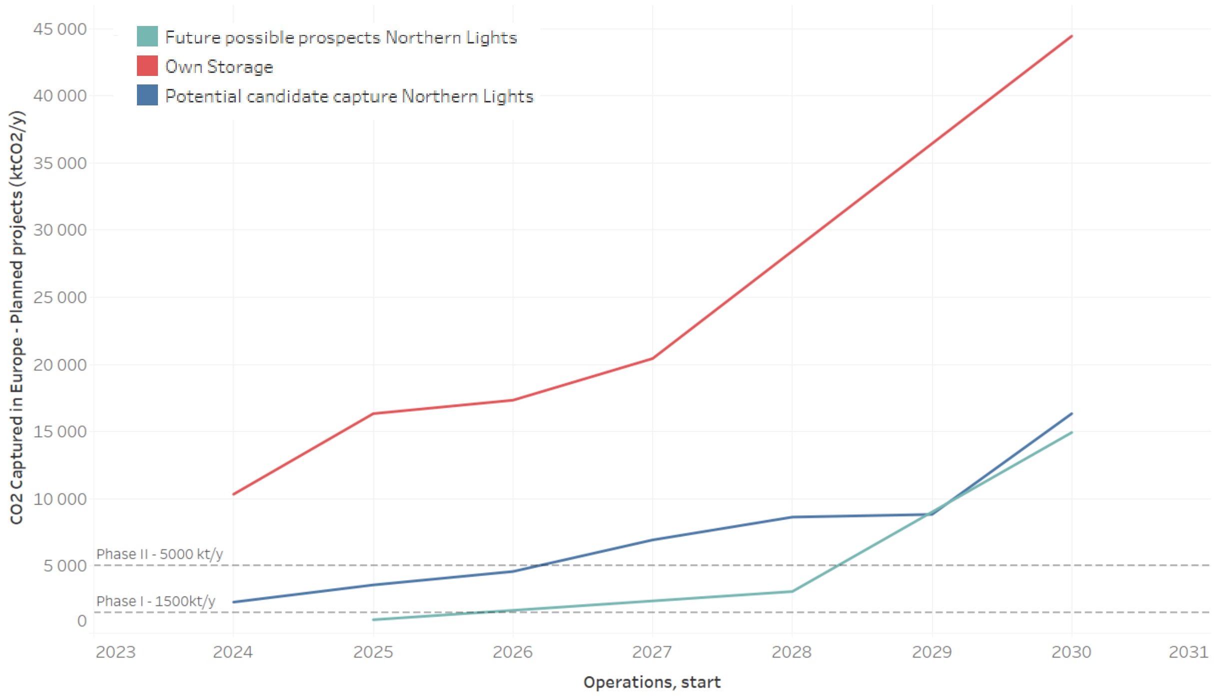
Source: Carbon Limits analysis

The 41 planned projects represent the whole range of sectors investigated in chapter 2, not only the cement and waste-to-energy sectors where CCS is the main option to reach net-zero emissions. This indicates that CCS is being explored by industries with multiple abatement options including iron and steel, chemicals/petrochemicals, refining, power and heat. Notably, blue hydrogen production is planned in many of these sectors, including refineries, chemicals, and other industry use.

Planned capture volumes and storage demand

Based on the timeline of each of the 41 projects, we have assessed the total CO_2 capture volumes towards 2030 and the associated need for annual storage. Figure 46 shows the results of this assessment with planned captured volumes per year and category, at the European level.

Figure 46: CO_2 capture capacity from planned projects 2023-2030 – annual volume in $ktCO_2$



The planned capture volumes are illustrated as individual lines for each of the three categories.

Source: Carbon Limits based on information from Northern Lights' project, interviews, and public databases

As can be seen in Figure 46, the first projects could start operation in 2024. The red line shows capture from projects planning to develop their own transport and storage solutions, while the blue line shows capture volumes from projects which may use Northern Lights capacities for transport and storage. Accounting for the uncertainties in timelines and volumes associated with each project, between 20 and 60 $MtCO_2$/y could be captured, transported and stored in the EU by 2030.

This does not include the 22 additional projects at earlier planning stages, which are represented by the green line. The green line indicates capture volumes from projects in earlier stages of planning that could possibly come as additional volumes. These have more uncertain timelines, but could represent an additional 15 $MtCO_2$/y for Northern Lights transport and storage if realised.

Compared to the storage capacity of Northern Lights, we see from the figure that the planned capture projects, if realised, could quickly fill up phase I (1.5 $MtCO_2$/y) capacity, while phase 2 capacity (5 $MtCO_2$/y) could also be filled within few years.

Box 9: CO_2 volumes of planned projects, relevance of learning from the full-scale project

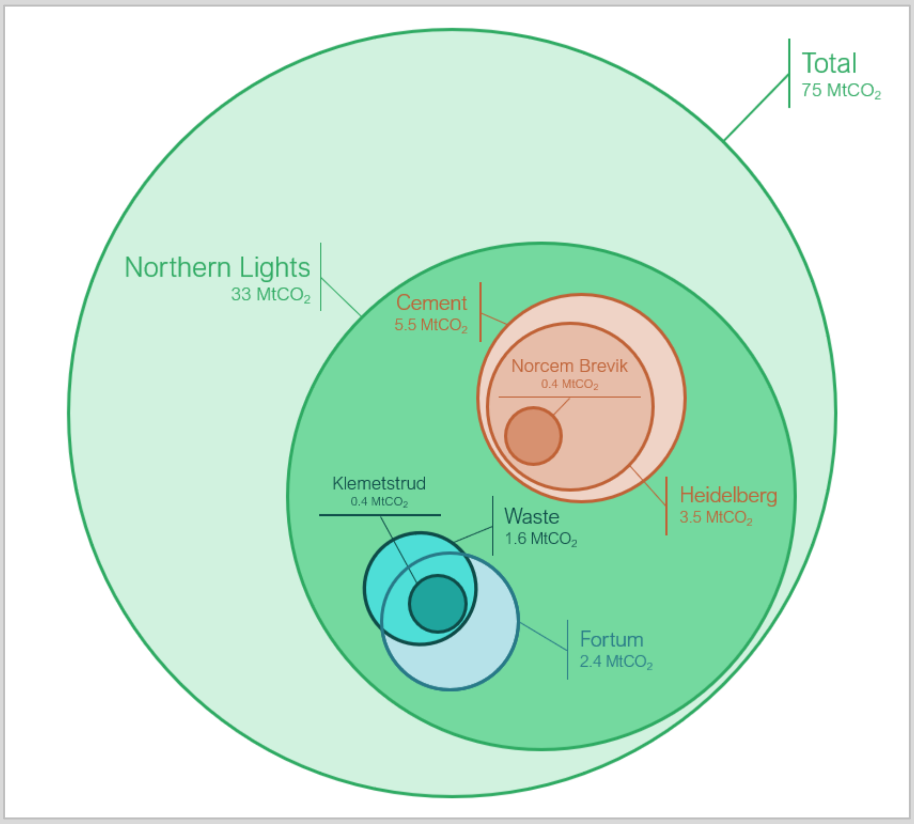
CO_2 volumes of planned projects, relevance of learning from the full-scale project

Based on the review of planned projects, we can illustrate the CO_2 capture volumes which could be most directly impacted by learning from the Norwegian full-scale project. Norwegian technology suppliers and contractors involved in the full-scale-project are participating in the development of projects in other sectors as well and would benefit from the Norwegian experience to increase competitiveness of their solutions.

On the capture side, both Norcem and Fortum Oslo Varme at Klemetsrud are illustrated in the small circles. Each of these captured projects can provide learning for future capture projects within their companies and within their sector, where planned volumes are illustrated in the larger circles.

Many planned projects depend on Northern Lights for CO_2 storage, illustrated in the dark green circle.

Figure 47 - Relative impact of the full-scale project by 2030 in EU 28 + Norway



Funding opportunities for planned CCS projects

At the time of writing, the EU emission reduction targets for 2030 are not set, and future EUA prices are very uncertain. In absence of sufficient carbon prices to trigger an investment decision, most of the projects would depend heavily on EU funding mechanisms, apart from a few that could receive national support (e.g. projects in Denmark, the Netherlands, and the UK). The Innovation Fund and the Connecting Europe Facility (CEF) will be important funding sources for these projects.

Until 2030, the Innovation Fund will have an estimated EUR 10 billion auction revenues at its disposal, based on an assumed EUA price of 22 EUR/tCO_2. CCS is one of the five topics that can be funded under the Innovation Fund, CCU being another one (cf. section 3.3.2).

CEF funding for energy could amount to EUR 8.7 billion for the 2021–2027 period, which is approximately 1.1 billion EUR/y. CO_2 networks are one of the four areas eligible for funding from this source.

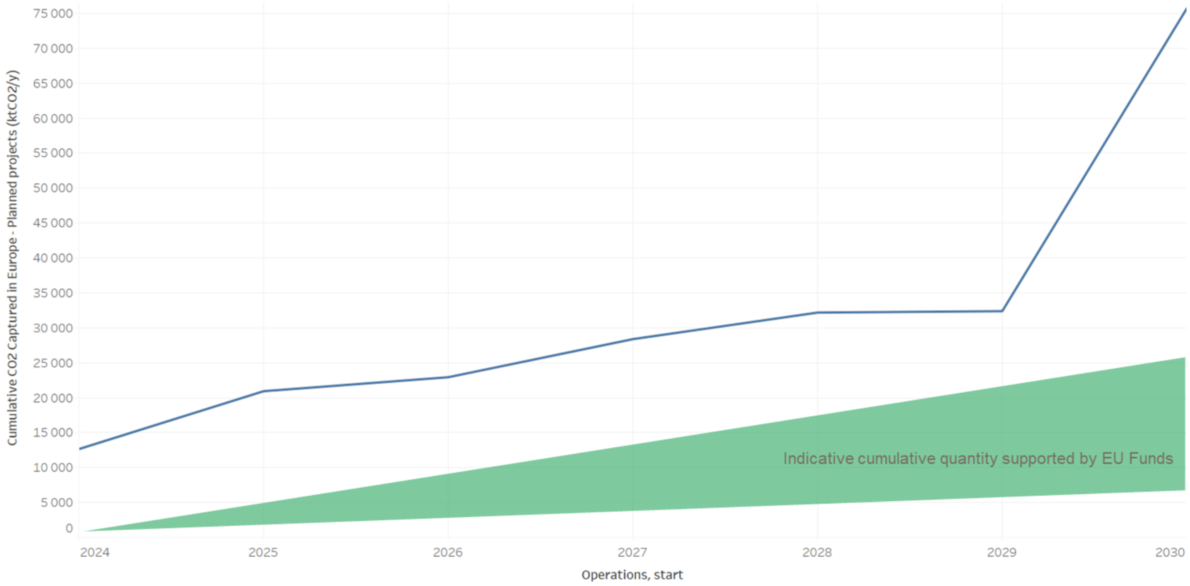
While different parts of the CCS value chain are eligible for funding, these funds are not earmarked for CCS. Both the Innovation Fund and the CEF cover a range of different topics with funding needs. Therefore, the amount of EU funding available for CCS projects will depend on the competition between the applications for a range of different project types.

To illustrate the scale of available funding we assume that CCS gets a share of the funding corresponding to the number of topics in each source (25% for CEF, and 20-40% for the Innovation Fund) a total of EUR 675 million could be allocated to CCS projects on a yearly basis from 2021 to 2027. This figure is equivalent to the cost of an additional 1–3 MtCO_2/y project per year[215], depending on the sector in which CCS is applied and the EUA prices.

If we then assume that capture projects start operation four years after funding is granted, by 2030, capture of 7–21 MtCO_2/y could be supported by the EU through the mechanisms in place. This is far lower than the cumulative potential of planned projects of up to 75 MtCO_2/y. These calculations are uncertain, and should be used with caution, but indicate that there are likely more projects than there is available funding. As discussed in section 3.3.4 and 3.3.5, some increased funds under the EU Recovery Package could potentially be allocated to support CCS, though it is unclear which mechanism would be used.

[215] This is based on a rough calculation, considering the following assumptions: Assuming that CCS gets a share of the funding corresponding to the number of topics in each source (25% for CEF, and 20-40% for the Innovation Fund) a total of EUR 675 million could be allocated to CCS projects on a yearly basis from 2021 to 2027. The innovation fund may support up to 60% of eligible (extra) costs, while CEF ranges from 50-75%. Assuming that the funds together represented 60% of eligible costs, the total extra costs would be about EUR 1.1 billion. If the EUA price increases, there will be two effects: Projects will be more profitable due to higher alternative costs of emissions, decreasing their need for external funding to close the funding gap. Furthermore, EUA price increases would increase the budget of the Innovation Fund and allow for support of more projects. Assuming different EUA price ranges until 2030 (EUA price of 22 EUR/tCO_2 for the period 2020–2030 and a linear increase from 22 to 52 EUR/tCO_2), we find a range of total costs which could be supported each year. The CCS capacity supported is calculated from abatement costs in different sectors, resulting in a range between 1 and 3 Mt CCS capacity supported per year.

Figure 48: Cumulative CO_2 captured quantity in Europe - Planned projects compared to uncertain estimates of CCS capacities supported by Innovation Fund and CEF

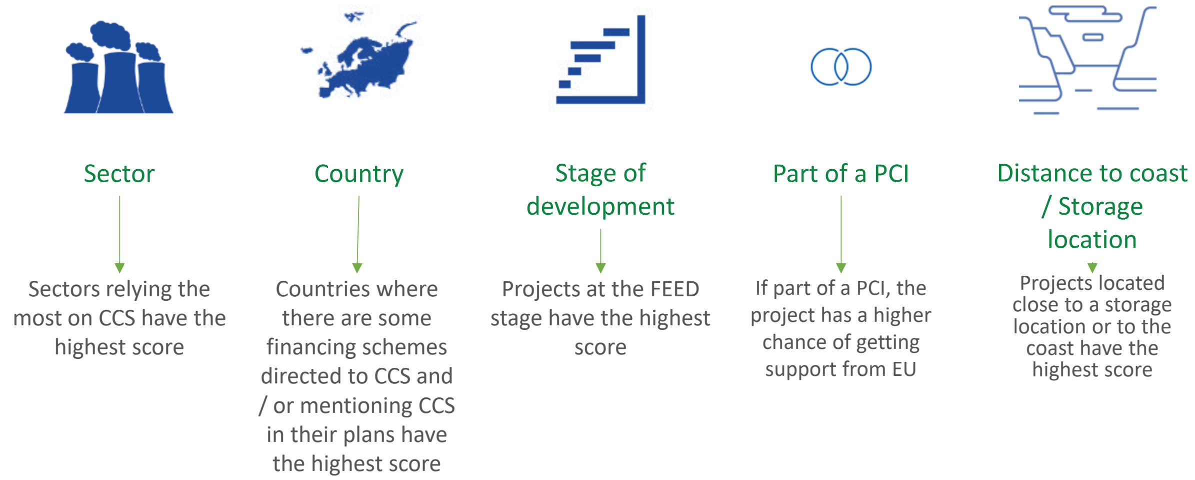


Source: Carbon Limits analysis

Some countries offer national funding schemes that are open to CCS applications. Certain projects in these countries have emphasised that they would primarily rely on these funding schemes, requiring less EU support. Furthermore, there is uncertainty on EU financing of UK projects beyond 2021. The cumulative capture potential of planned projects which intend to rely on EU funding is estimated to be around 50 $MtCO_2$/y.

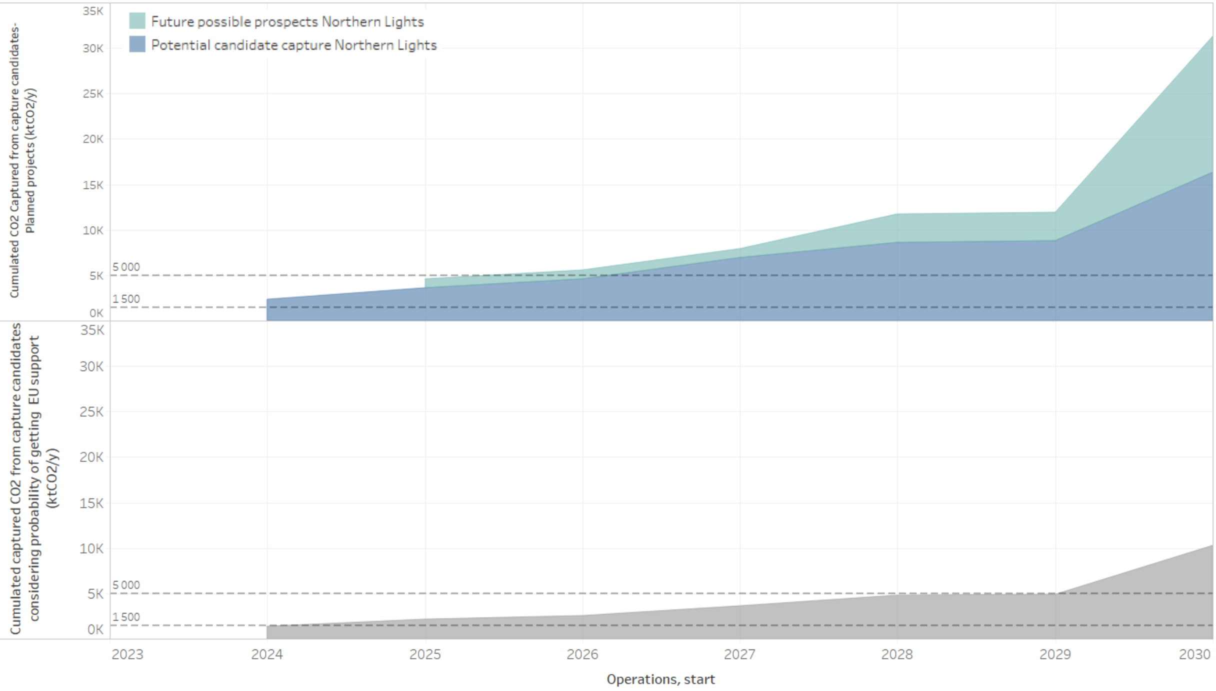
To further assess the likelihood that projects planning to store at Northern Lights receive EU funding, we have assessed the likelihood that each of the planned projects will be realised based on country, sector, project maturity, location and whether it is part of a "Project of Common Interest"). For each project a probability of realisation was estimated based on these factors, as illustrated in Figure 49.

Figure 49: Criteria used to assess the probability of realisation



The graph in Figure 50 shows the results. According to these uncertain calculations, EU-funding could support projects equivalent to the rest of phase I capacity quickly, and phase II capacity before 2030.

Figure 50: Cumulated CO_2 captured that could be sent to Northern Lights – Top: Planned – Bottom: Taking into account probability of realisation and of getting funding



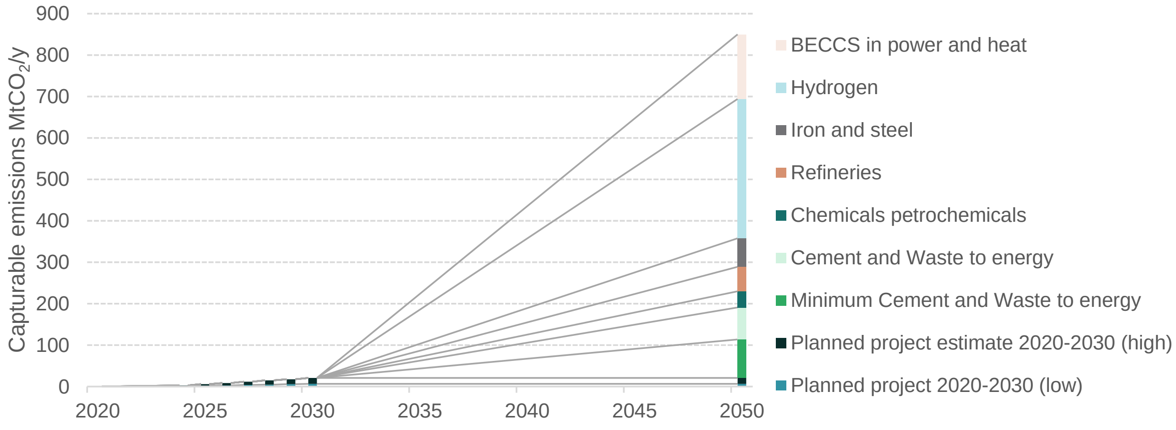
Source: Carbon Limits analysis

Since EU funding covers only up to 60% of extra costs of those projects, this does not necessarily mean that these projects would be realised. The remaining 40% of extra costs would have to be covered by other public financing incentives or private investment. Private investment could potentially be motivated by a combination of factors: the project's strategic value, the ability to pass increased costs over to consumers (e.g. through sale of low carbon products), or non-economic incentive mechanisms such as fuel mandates. The weight and significance of each of these factors is project-dependent, and it is not possible to make any strong conclusions on whether EU financing would be sufficient to trigger investments in these projects.

However, even with the limitations of the share of EU funding, the capture projects have expressed high interest in transport and storage with Northern Lights. In interviews, representatives of the capture projects have highlighted that access to storage capacity is an important uncertainty and a barrier to go ahead with the project. Guaranteed access to storage from 2024 onwards would be a major enabler for the capture projects. Northern Lights is currently the most developed project to plan transport of CO_2 by ship. The other two projects which are at a relatively advanced stage, Porthos in the Netherlands and Acorn in the UK, plan initially to rely on pipelines for the transport of CO_2.This excludes many projects relying on sending CO_2 to a terminal to access the storage part of the value chain. Northern Lights is among the most advanced storage project in Europe and is therefore well positioned to be a first mover and to be an essential enabler for several capture projects before 2030.

To compare the development of projects in the short term with the estimated capturable quantities from chapter 2, we can see what different possible pathways could look like. Figure 51 illustrates the capturable CO_2 quantities discussed chapter 2, compared to the possible EU-funded projects between 2020 and 2030. Depending on future developments in the EU, member states and industries, capturable quantities could range between 90 $MtCO_2$/y to above 800 $MtCO_2$/y in 2050. For the minimum scenario of 90 $MtCO_2$/y on waste-to-energy and cement production, this would require on average, a scale up of 3 $MtCO_2$/y in the years 2020-2050, or 4$MtCO_2$/y in the years 2030-2050.

Figure 51: Planned projects with EU funding 2020-2030 and capturable CO_2-quantities by 2050



Source: Carbon Limits and THEMA analysis

These levels can be compared to the country-specific targets. Only France and UK have quantified their CCS requirements by 2050 and these targets reach 190 $MtCO_2$/y (mostly driven by the UK targets). They are above the minimum CCS requirements for all EU as they include some BECCS and blue H_2 for UK.

6. Assessment of benefits from the Norwegian full-scale CCS project

6.1 Introduction

As pointed out in earlier assessments, the Norwegian full-scale CCS project potentially has a significant demonstration value as being the first project in Europe with full-scale industrial capture, flexible ship transport and offshore storage as integrated parts. The two capture facilities considered in the Norwegian full-scale project, in cement and waste-to-energy, are also in the two sectors where CCS is considered the only abatement option to achieve deep emission reductions. These sectors are represented in all the investigated countries.

The Norwegian full-scale CCS project has the potential on a European scale to reduce barriers to future CCS projects and provide new opportunities for Norwegian industries. The scale of such benefits depends on the level of future CCS deployment. Policies shaped in Europe have a significant influence on these beneficial effects, and therefore on the value of the full-scale project. These barriers could be related to acceptability, regulatory issues, costs, or lacking infrastructure for transport and storage of CO_2. In addition, a successful demonstration of the Norwegian full-scale project could influence policies in the EU and member states that increase the role of CCS, thereby facilitating deployment of additional future projects, and increasing the benefits of the full-scale project.

In this chapter, we assess to what extent the increased ambition level for emission cuts affect the benefits of the full-scale project and explore some of the main benefits. The assessment is based on the analysis of the preceding chapters; i.e., the possible scale and competitiveness of CCS within different sectors (chapter 2), targets and policies initiated at the EU level (chapter 3), policies and plans at the national level of nine countries (chapter 4) and a review of CCS projects under planning (chapter 5). The main question is not the absolute value of the various benefits, but to what extent the increased EU climate policy ambition level increases these benefits.

Four categories of benefits are assessed in the analysis:

1. Demonstration and facilitation value
2. Value of stored emissions
3. Productivity gains
4. Industrial development

In line with earlier assessments, we distinguish between the demonstration and facilitation effect, and the productivity gains of the project. The demonstration and facilitation effect is the impact on the first hurdle for CCS as a considered abatement solution, i.e. the effect that the successful implementation of the project demonstrates the technological feasibility of the solution in full scale and in real life, and thus facilitates the realisation of other projects. The productivity gains relate to the scope and scale of the demonstrated solution. In addition, we assess the value of the project-specific captured and stored CO_2, and the potential values accruing from increased value creation for the Norwegian economy, i.e. industry development and the value of Norwegian gas.

In the assessment, it is important to keep in mind and take into account that the value of the full-scale project is attributable not only to the integrated project, but also to the different elements of the project. The change in the value of the different elements due to increased emission reduction ambitions can hence, also vary.

6.2 Demonstration and facilitation value

As pointed out in earlier assessments, the Norwegian full-scale CCS project potentially has a large demonstration value being the first project in Europe demonstrating full-scale industrial capture, flexible ship transport and offshore storage as integrated parts. In addition, the two facilities with carbon capture, cement and waste-to-energy, are in the two sectors where CCS is the only abatement option to achieve deep emission reductions (cf. chapter 2). Projects in these sectors are also presented in the review of planned projects covered in chapter 5.

The question at hand is to what extent the demonstration value of the full-scale project increases due to the increased ambition level in the European Green Deal (EGD).

The demonstration value is basically attributed to four sub-elements:

1. Demonstration of CCS as a safe and feasible solution
2. Facilitation of future projects
3. Regulatory learning
4. Commercial learning

Demonstration of CCS as a safe and feasible mitigation option

By successfully implementing the full-scale project, the solution is demonstrated as a safe and feasible mitigation option which in turn is likely to increase the interest in the technology by politicians, industry, and investors. This value does however not necessarily change with the adoption of the EGD – even with a less ambitious climate policy target, this effect would be realised (the value does increase if it applies to a larger volume, which is further explained in the discussion of the productivity effect.) A notable difference in the demonstration value does however apply to the demonstration of capture from a waste-to-energy facility and from cement production.

Hence, the value of demonstration of the feasibility of carbon capture on these processes increases substantially with the tightening of the target to net-zero emissions in 2050.

Impact on policies: As the analysis in chapter 3 and 4 shows, EU and national policies for the realisation of the EGD ambitions are at a formative stage. Multiple policies which influence CCS and hydrogen are to be carved out within a relatively short time span. A positive demonstration of a CCS value chain through the Norwegian full-scale project has the potential to impact policies and reduce some of the current policy barriers to CCS deployment.

By demonstrating the feasibility of the solution, politicians and regulators are more likely to adapt policies and carve out targeted measures towards CCS. The increased EU climate policy ambition implies that high-cost abatement options (including negative emissions) are needed (cf. chapter 3). The realisation of the full-scale project (and the possible associated cost reductions, as we discuss in the section on productivity gains) is likely to increase the interest in CCS as an efficient long-term solution, thereby attracting political attention and spurring political action.

Public acceptance: Acceptability remains a barrier for CCS in the EU and several member states. Public opposition to CCS has contributed to the cancellation of past projects and may be a detriment to future developments. For example, in some of the modelling exercises discussed in chapter 3, CCS deployment in power generation was restricted due to low acceptance. By demonstrating CCS as a safe solution and by offering offshore storage, such barriers could also be reduced. This effect is not necessarily increased due to the adoption of more ambitious climate policies, but increased public acceptance is likely to be an important factor for the change of general policies towards CCS.

Facilitation of future projects

The full-scale project will not only demonstrate an integrated value chain for CCS, it will also establish a CCS infrastructure for the transportation and storage of carbon dioxide that other infrastructure projects will benefit from.

While the demonstration value is that the solutions and learning from the full-scale project can be copied by other projects, the facilitation value is associated with the physical infrastructure that is established as part of the project. The project establishes an infrastructure that is currently missing, which constitutes a major barrier for capture projects without access to own or other storage solutions. The access to transportation and storage offered by the Northern Lights project therefore has as a facilitation value in addition to the demonstration value of the project.

Without available storage and transport solutions, industrial actors would not be able to implement CCS projects. While close-proximity to CO_2 storage is an option for some large or clustered projects, the Norwegian full-scale project facilitates development of other projects in Europe by establishing ship transport routes to a large geographical area and provide storage capacities. Interviews with representatives of relevant projects have highlighted their dependence on Northern Lights' ship-based transport solution as a key facilitator. In the longer term, many facilities located far away from geological storage possibilities, and multiple countries have pointed to Norwegian storage as a storage solution.

Regulatory learning

Reaching the EU ambition of net-zero emissions requires a development of a regulatory framework, which is also demonstrated by the ongoing profound review of climate policy framework in relation to the adoption of more ambitious climate targets. With the increased ambition, it becomes more relevant to incentivize carbon removals where BECCS could be a key technology for negative emissions. Currently, regulations in EU-ETS and elsewhere do not incentivise capture of biogenic CO_2. Since the Norwegian capture projects involve capture of significant shares of biogenic emissions both from Norcem and from Fortum Oslo Varme, experience from these projects would be early contributors to regulatory learning on this issue. The value of regulatory learning increases as the likelihood of BECCS as part of the long-term solution increases.

The regulatory learning benefit of the full-scale project appears to already have had an effect on the most pressing barriers to cross-border ship transport of carbon dioxide. Under the framework of the ETS directive, CO_2 transport is defined as transport by pipeline only, and there is currently no legal clarity whether captured CO_2 transported by ship for storage would qualify for exemption from the obligation to surrender EUAs. The Norwegian full-scale project has contributed to increased awareness in the European Commission on this issue, and the Commission is expected to provide clarity on this matter.

A similar issue arises with the TEN-E regulation, under which European energy infrastructure projects of common interest are defined and could receive support. For CO_2 transport networks, only dedicated pipelines or related equipment are defined, and there is little clarity which parts of a ship-based transport and storage chain would qualify for support. However, the Northern Lights project has qualified as a project of common interest and is eligible to apply for support under the Connecting Europe Facility programme.

The London Protocol has been a key regulatory barrier to cross border transport of CO_2 for storage purposes. This provision was amended in 2009, which allowed for cross border transport of CO_2 for geological storage purposes. However, for the amendment to enter into force, two thirds of the Contracting Parties would have to accept the amendment. Currently at 53 members, as of 2019, only six of 53 parties had ratified the amendment, of these Norway, UK, Netherlands, and Finland. Denmark, Germany, Ireland are also signatories of the London protocol, but as of October 2019 not ratified the amendment. Sweden ratified the amendment in June 2020, Belgium has stated plans for ratification in 2020, while France has indicated that it will ratify. In 2019, as a result of a proposal from Norway and the Netherlands, a provisional application of the amendment was adopted, allowing for countries to give consent to cross-border transport of CO_2, without breaching the protocol prohibition on export of waste. There is still a need for bilateral agreements between countries under the provisional application of the amendment.

As seen above, many of the regulatory barriers are in the process of being solved or gaining more clarity, partially due to the need from the Norwegian full-scale project. As such, the project has already contributed to the reduction and removal om important regulatory barriers before the project is realised.

Commercial learning

The Norwegian full-scale CCS project covers interdependent activities by different commercial actors along the value chain and has provided important commercial learning. Active and innovative private actors are of critical importance for large scale deployment of CCS, and the experience from the Norwegian full-scale project could provide learning on commercial models to increase value from CCS, both on the industrial production facilities and the CO_2 value chain.

New business models to enable higher market value for products produced by CCS are under development. The planned proposal on the Carbon Border Adjustment Mechanism and future initiatives under the Industrial Strategy and Circular Economy Action plan could influence the value of commercial learning and establishment of new business models which increase the market value of sustainable products. Once standards and product labels are established and recognized in the market it will be in the interest of companies engaged in CCS to pursue business opportunities which can reward the environmental credentials of their products. Empirical studies show that the price differentials for end products (e.g. cement or specific concrete products) are relatively modest.

One issue which increasingly is coming to the forefront is the development of methodologies and standards for accounting for and reporting lifecycle emissions of products manufactured using CCS (e.g. cement and steel products). Some international industry associations (e.g. WBCSD) are active in this field.

The availability of new low carbon products produced with CCS allows for procurement processes to have stricter criteria, e.g. cement in construction projects, adding value to low carbon production with CCS. Commercial learning through development of new business models could allow industry to pass the extra costs of CCS on to customers in novel ways.

The cross-border transport of CO_2 and storage by the Northern Lights will add to this, by becoming an early actor in trade of captured CO_2 and may contribute to the establishment of a market.

6.3 Productivity benefits

In addition to the potential effect of demonstrating the realism of a fully integrated CCS value chain, successful implementation of the full-scale project is likely to realize learning effects that reduce the cost of all the elements of the full-scale project. The value of this learning increases with scale. As we have demonstrated in the chapters above, the increased climate ambitions and policies in Europe, potentially increases the scope for CCS in Europe significantly. Thus, the recent climate policy developments clearly increase the productivity value of the full-scale project. By how much depends on the competitiveness of CCS in different sectors.

The productivity elements consist of three sub-elements:

1. Cost reductions due to learning
2. Transport and storage capacity for other projects
3. Cost reduction due to scale effects of transport and storage

Cost reductions due to learning

Cost reductions for future projects which are a result of technology development and large-scale deployment often have higher value to society than for the commercial actors alone. The knowledge and know-how gained from a CCS project has a strategic value to the project owners themselves, but learning benefits also disseminate to all future projects as reduced cost and risks. This type of externality is a common feature of technology development, and the primary argument for government intervention to promote sufficient investments in technology from a societal perspective. It can be difficult to assess the value of technology development a priori, due to uncertainties on the success of a demonstration project, and to what degree the technology is later deployed.

The Norwegian full-scale CCS project is an early-mover project and as such provides learning and cost reductions to the benefit of future projects. This value depends on the expected number of realised future projects. Since the increased climate ambitions of the EU and member states are expected to increase deployment, this value can be expected to increase significantly.

Based on analysis of the recent developments in EU and member state policies in chapters 2, 3 and 4, we have assessed different capturable volumes in the EU, further described in chapter 2 and 5. These pathways are used to assess the benefit of the Norwegian full-scale project with two capture sites on cost reductions due to learning from deployment using a CCS cost curve developed by DNV-GL.[216]

In a scenario where the minimum amount of CCS is applied in EU28 for net-zero emissions, as described in chapter 2, fossil emissions from these cement and waste-to-energy sectors represent 90 $MtCO_2$/y and are captured with CCS. In a pathway where CCS capacity increases gradually to 90 $MtCO_2$ per year in 2050, the net present value of future cost reductions would be about EUR 330 million. In a high pathway with 340 $MtCO_2$ captured per year in 2050 from cement, waste-to-energy, chemicals/petrochemicals and refineries, the net present value would be about EUR 1.1 billion. The method[217] used to estimate this is conservative, for two reasons: First, while the DNV-GL cost curve is a CCS-industry wide approximation based on empirically derived costs for different industries, the actors in the Norwegian full-scale project are required to actively disseminate knowledge and know-how to future projects. It can therefore be assumed that the project's contribution to reduced costs would be higher than an "average" project without these requirements. Second, the Norwegian full-scale project introduces a novel value chain which includes capture from two different industries, ship-based transport and possibilities for third party storage. Either or both factors could greatly increase the total benefit of cost reductions for future projects.

Transport and storage capacity to other projects

The implementation of the full-scale project implies establishment of carbon dioxide infrastructure which by offering available transportation and storage capacity, facilitates the development of CCS projects without access to own storage or where storage access is uncertain. Thus, the Norwegian full-scale project may facilitate development of projects other than the domestic ones by establishing ship transport routes to a large geographical are and provide storage capacities.

Interviews with representatives of relevant projects have highlighted their dependence on Northern Lights' ship-based transport solution as a key facilitator. The mapping of projects in chapter 5 has revealed that there is a high interest in Northern Lights as a storage facility. To what extent the increased climate ambitions of the EU and member states increase the facilitation value of the Northern Lights project, however, depends on whether the capacity would have been filled even without the increased ambition. Our assessment is that the likelihood of full capacity utilization from an earlier time increases somewhat due to the EGD, thus the facilitation value also increases.

In the short term, the mapping of projects in chapter 5 has revealed that there is a high interest in Northern Lights as a storage facility. With about 17 $MtCO_2$/y from potential capture candidates and an

[216] It is important to note, that only the future EU28 deployment pathways are assessed here. The benefits to future CCS projects outside the EU are not taken into account here.

[217] The calculation method is described in appendix, section 7.3

additional 15 $MtCO_2$/y of prospective capture sites, the opportunities are significantly higher than storage capacities in phase 1, and also a future phase 2 with 5 $MtCO_2$/y. As a first mover the Norwegian full-scale CCS project is particularly well placed to be a preferred option for companies seeking a location for distant CO_2 storage. Capturable emissions can be considerable even when limited to facilities close (25 km or less) to good ports at sea, with about 120 $MtCO_2$/y of capturable industrial emissions from the countries reviewed in chapter 4.

In the longer term, geological conditions and political barriers restrict the capacity for nearby storage in many countries. These countries represent a large share of capturable industrial CO_2 volumes in the selected countries, ranging from 50 to 150 $MtCO_2$/y (low and high capturable volumes respectively). A cost-efficient solution can in many cases be transported to a port and ship transport, before a pipeline network is developed, to the Norwegian Continental Shelf for storage.

Cost reduction due to scale effects of transport and storage

In addition to the cost reductions associated with technology deployment, CCS transport and storage infrastructure also benefits from economies of scale, i.e. that it is more cost effective for multiple actors to use a common infrastructure. The Northern Lights project allows for storage of third-party volumes, using a flexible network of transport ships. This allows for reduced cost of transport and storage for additional capture projects, which otherwise would need to develop solutions at a less optimal scale. In its first phase, the Norwegian full-scale project involves capture of 0.4-0.8 $MtCO_2$/y, and the establishment of transport and storage with capacity up to 1.5 $MtCO_2$/y. Further capacity increases of storage and transport up to 5 Mt require new investments, but with significant returns to scale, reducing the transport and storage costs per tonne. Increased capacity utilisation would provide shared benefits for the Northern Lights project and potential capture projects. How the benefit is shared between the parties depend on tariffs and contracts.

With potential for further scaling up of Northern Lights, to increased storage volumes, the cost reductions have the potential to benefit future capture projects further. From the assessment in chapter 5, we have seen that there is increased interest, with 11 capture projects planning to use Northern Lights for transport and storage, and that an additional 22 projects are potential future prospects. Based on the assessment of EU policies in chapter 5, with the heightened ambitions for 2030 and 2050, it can be concluded that the likelihood of realisation increases.

6.4 Value of CO_2 emissions stored

Impact of European policy development: There are multiple approaches to determine the value of the emissions that are stored in the full-scale project. The two capture plants are in different sectors, differ with regards to emission regime (ETS and non-ETS), and capture significant shares of biogenic CO_2. One approach could be to set a value based on the cost of emissions for the different sectors, which could differ greatly between the two capture plants. Other approaches could involve estimating values associated with achieving a certain national or international target or associated with marginal abatement costs. For the purpose of this task, the increased target in 2030 and 2050 are likely to increase the price of emissions and increase the value of the benefit of stored CO_2.

Observations: The willingness to pay for emissions reductions as manifested by actual carbon pricing can be an indication of value of storing the emission. In chapter 3, we saw that in the long-term strategy scenarios the European Commission apply a higher stylised carbon price in the ETS for the scenarios achieving net-zero emission than the scenarios achieving only 80% emission reduction by 2050. Both groups of scenarios start at 28 EUR/tCO2 in 2030, but while the price increase towards 250 EUR/tCO2 with 80% emission reduction, it increased further up to 350 EUR/tCO_2 in the net-zero scenarios. In the shorter term, some analysis suggests that the increase in the emission reduction target for 2030 from 40% to 50% and possibly up to 55% could lead to EUA prices increasing from 29

EUR/tCO_2 at 40% emission reduction up to 52-76 EUR/tCO_2 with an increase to 50-55%. This illustrates that the willingness to pay for emission reductions could increase substantially as a consequence of a more ambitious EU climate policy.

6.5 Industrial development benefits

Three ripple effects related to industrial development in Norway has been identified as potential benefits of the Norwegian full-scale project:

- Increased value of CO_2 storage on the Norwegian continental shelf
- Increased value of the Norwegian natural gas resources
- Increased commercial competence of Norwegian CCS industry

The effect of all three industrial development benefits that can result from the realisation of the full-scale project has increased as a result of recent European policies.

Increased value of CO_2 storage on the Norwegian continental shelf

Impact of European policy development: A more ambitious European climate policy towards 2030 and 2050 is likely to increase the scope for CCS and the demand for carbon dioxide storage. The size of the benefit depends on the expected demand for CCS in areas where transport of CO_2 for storage in Norway is competitive with other storage solutions. As found in this report, recent policy developments in Europe increase the expected role of CCS as an abatement option. Hence, the expected value of this benefit effect is increased.

Observations: The extent to which Norwegian CO_2 storage becomes a scarce resource depends on the realised capture volumes, and the availability of storage options more easily available from the capture site than Norway. We have seen in chapter 4 that the geological resources for CO_2 storage are not evenly distributed between countries, and that some countries would likely require storage outside their borders either due to a lack of physical storage capacity or due to acceptability issues.

The uncertainty of CCS deployment in the EU between now and 2050 is high, although the net-zero target clearly increases the likely demand for carbon dioxide transport and storage. For industrial production and waste-to-energy, we have estimated a capturable range between 170 and 340 MtCO_2 stored per year in 2050. If blue hydrogen production contributes to a significant share of hydrogen demand, and BECCS is implemented the range could increase to over 800 MtCO_2 per year. With a capacity of 1.1 GtCO_2 already assessed as suitable for long term offshore storage, and an additional 67 GtCO_2 effective capacity which could potentially be used[218], all captured CO_2 volumes in the EU over the foreseeable future could likely be stored in Norwegian geological formations, even in the high scenarios described in chapter 5.

However, countries such as the United Kingdom also have large storage capacities, with 78 Gt of likely theoretical potential in saline aquifers and oil and gas fields.[219] Other countries such as the Netherlands and Denmark also have significant offshore storage potentials.[220] If these theoretical potentials are confirmed to have practical applicability, it does not appear that geological storage capacity would be a limiting factor for CCS, and the value of these resources would be less dependent on their scarcity.

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[218] Norwegian Storage Atlas, available here: https://www.npd.no/en/facts/publications/co2-atlases/co2-storage-atlas-norwegian-north-sea/

[219] UK Online Storage Atlas, available here http://www.co2stored.co.uk/home/index

[220] Geocapacity final report

There are significant economies of scale related to the infrastructure for CCS. In terms of economic efficiency, it will therefore be more cost-effective to coordinate a transport and storage solutions than for each project to establish a full value chain. While other countries are likely to be able to offer CO_2 storage, the geological storage capacity in Norway, offered by the full-scale project, could have a competitive advantage as the marginal cost of increased capacity is likely to be lower than the establishment of capacity at other sites.

Increased value of natural gas resources in hydrogen production

Impact of European policy development: The increased climate policy ambitions of the EU and accompanying strategies indicate a significant role for hydrogen in the energy system. Although the long-term emphasis is put on green hydrogen, blue hydrogen is expected to play a role in the medium to short term. The value of this benefit effect increases with the expected demand for low-emission hydrogen in Europe. The full-scale project can indirectly increase the demand for blue hydrogen by offering transportation and storage capacity for captured CO_2 from hydrogen production, and by improving the competitiveness of blue vs. green hydrogen through cost reductions in transportation and storage.

Recent policy developments at EU and Member State level imply increased emphasis on hydrogen to decarbonise the economy. As part of the European Green Deal, the Commission is expected to present a Hydrogen Strategy and launch a Clean Hydrogen Alliance in July 2020, and several countries, including Germany, has developed their own hydrogen strategies and targets. Recent developments in Europe therefore increase the value of this benefit effect.

Observations: As we have seen in chapter 2, steam reforming of natural gas with CCS to produce blue hydrogen can be a competitive option compared to using electrolysis to produce green hydrogen.

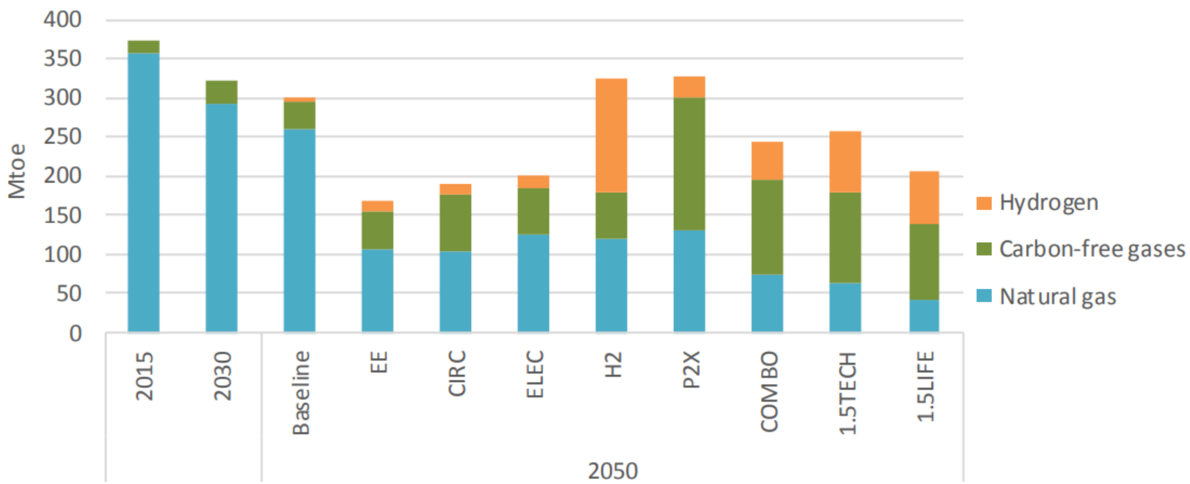
However, there is considerable uncertainty both related to the total volumes of future European hydrogen demand as well as to the extent to which blue hydrogen will be used to meet this demand. Expected policy decisions on EU and Member State level, notably the pending EU Hydrogen Strategy, is likely to impact both the volume and production technology preference. As we have seen in chapter 2 and chapter 3, a range of 0 $MtCO_2$ [221] and 465 $MtCO_2$ captured from hydrogen has been identified.

While highly uncertain, blue hydrogen production therefore has the possibility to represent a significant source of demand for natural gas in a net-zero future. The market share of natural gas held by Norwegian producers in such a future is also uncertain.

As we have seen in chapter 3, the EU long term strategy included different scenarios which achieve 80% emission reductions (ELEC, H2, P2X, EE, and CIRC), one 90% scenario (COMBO) and two net-zero scenarios (1.5TECH and 1.5 LIFE). Based on these scenarios, energy usage was modelled. With the increased ambitions to net-zero, the projected EU use of natural gas in 2050 is reduced. While the reduced imports of natural gas are 51–60% compared to 2015 levels in the 80% scenarios, the reduction is up to 81% in the net-zero scenario. Hydrogen represents a larger share than natural gas in both net-zero scenarios.

[221] Excluding own production in chemicals/petrochemicals and refineries.

Figure 52: Gas volumes in the EU in 2050 across scenarios.



Source: EC (2018) – A Clean Planet for All

Currently, there are barriers related to infrastructure for transport and storage of CO_2, as well as transport and storage of hydrogen. Early investments in CO_2 transport and storage infrastructure, which facilitate future blue hydrogen production, may reduce barriers and increase the likelihood of a hydrogen pathway using natural gas. Infrastructure allows realisation of commercially viable projects, allowing for cost reductions and increased competitiveness against green hydrogen production.

Potential for commercial development Norwegian CCS industry (technology providers & services)

Impact of European policy development: The full-scale project creates a basis for the development of and increased competence in the Norwegian CCS industry, which in turn can lead to increased commercial activity in Norway or for Norwegian actors. The benefit of this commercial and industrial development increase with the market for CCS technologies. As the recent EU and national policies increase the expected volumes of CCS in Europe, the value of the benefit effect is expected to rise.

Observations: More ambitious EU and member state policies increase the likelihood of CCS deployment. For the CCS technology providers, the Norwegian full-scale project demonstrates solutions which can have significant value for future sales of their technology. As we have seen in chapter 2, the cement and waste-to-energy sectors will be reliant on CCS if they are to achieve deep emission reductions. Since the two capture projects involved in the Norwegian full-scale project entails capture from one or both of those processes, the involved technology providers have a competitive advantage in these sectors. For example, each of the capture sites have optimized the heat usage of their capture units to the sector specific processes. While cement production involves waste heat which can be used for the capture project, the waste-to-energy plant recovers waste heat from the CCS capture unit is recovered and utilized in the production of district heating.

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7. Appendix

7.1 Summary of scenarios from the EU's long-term strategy

Long Term Strategy Options

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

7.2 Taxonomy on sustainable finance

Criteria for capture from anthropogenic emissions are that:

- "it enables the economic activity to operate under its respective threshold and
- It shows that the captured CO_2 will be offloaded to a Taxonomy eligible CO_2 transportation operation and permanent sequestration facility"

Criteria for transport of CO_2:

- Transport modalities that contribute to the transport of CO_2 to eligible permanent sequestration sites are eligible, only if the asset operates below the leakage/tonne of CO_2 threshold.
- Leakage/tonne of CO_2 transported from head(s) of the transport network to injection point(s) is <0.5%, and the CO_2 is delivered to a taxonomy-eligible permanent sequestration site or to other transport modalities which lead directly to an eligible permanent sequestration site are eligible.
- Assets or activities that enable carbon capture and use (CCU) will deem all the connected elements of an existing transport network ineligible.
- Assets which increase the flexibility and management of an existing network, without expanding the network to include carbon capture and use activities is eligible.

Criteria for storage of CO_2:

- Operation of a permanent CO_2 storage facility is eligible if the facility complies with ISO 27914:2017 for geological storage of CO_2.

Thus, according to the Taxonomy, the sustainability of investments in any part of the CCS value chain depends on the whole value chain being taxonomy eligible.

When it comes to the sustainability of manufacturing of hydrogen, the following thresholds apply*:*

- "Direct CO_2 emissions from manufacturing of hydrogen: 5.8 tCO2e/t Hydrogen in alignment with energy thresholds in the taxonomy.
- Electricity use for hydrogen produced by electrolysis is at or lower than 58 MWh/t Hydrogen
- Average carbon intensity of the electricity produced that is used for hydrogen manufacturing is at or below 100 gCO_2e/kWh (Taxonomy threshold for electricity production, subject to periodical update)."

It is specified that this threshold could be met both by the production of hydrogen from green electricity and through the usage of CCS technologies.

7.3 Calculation of productivity benefit of cost reductions

Cost reductions for future projects which are a result of technology development and large-scale deployment can be analysed as positive externalities of knowledge, since the value of the learning often will be larger than the actors can utilize alone. The knowledge and know-how gained from a CCS project has a strategic value to the project owners themselves, but also has value for all future projects as cost and risks are reduced. However, this knowledge and know-how is difficult to monetarize fully for the project owner, and they would therefore invest less than would be optimal from the societal viewpoint. This type of externality is a common feature of technology development but does not necessarily mean that all technology development is profitable from a societal perspective. It can be difficult to assess the value of technology development a priori, due to uncertainties on the success of a demonstration project, and to what degree the technology is later deployed.

Development of new climate technologies can be analysed using the figure below. The figure represents the mitigation cost per tonne of CO_2 at different levels of deployment. In the figure, the initial costs of the direct reductions of emissions are substantially higher than the cost of emissions and would not be cost-effective to implement as a one-off venture. However, the technology has a potential to reduce emissions at a cost below the cost of emissions, illustrated by the cost curve of technology development. The indirect effect of the first project is its contribution to reduced costs for subsequent projects.

Figure 53 - Cost curve of climate mitigation technologies

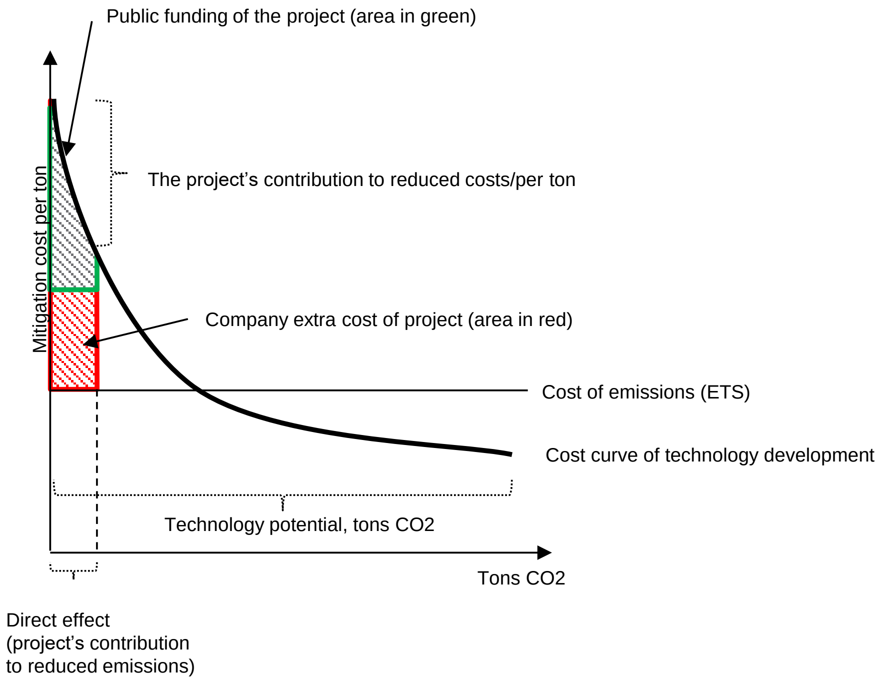
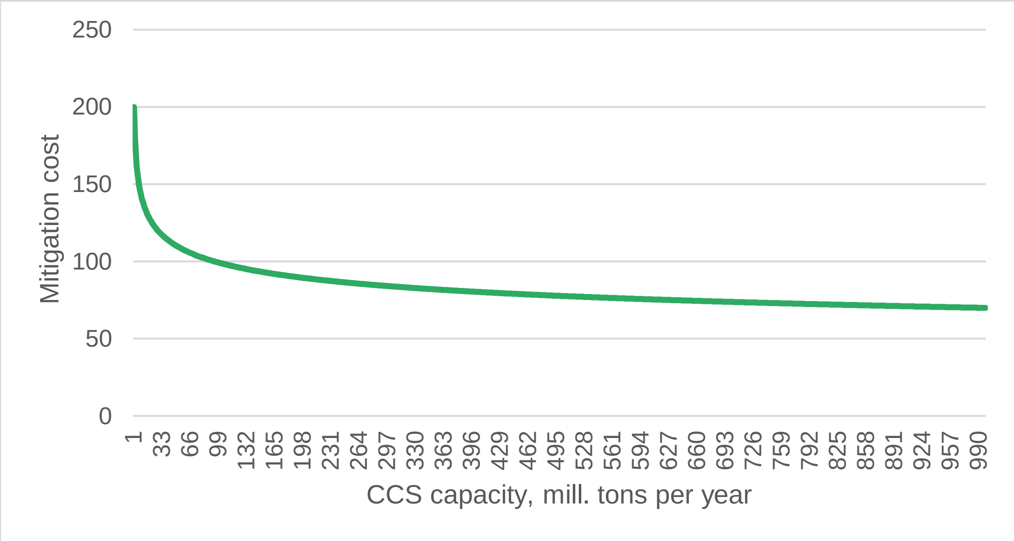
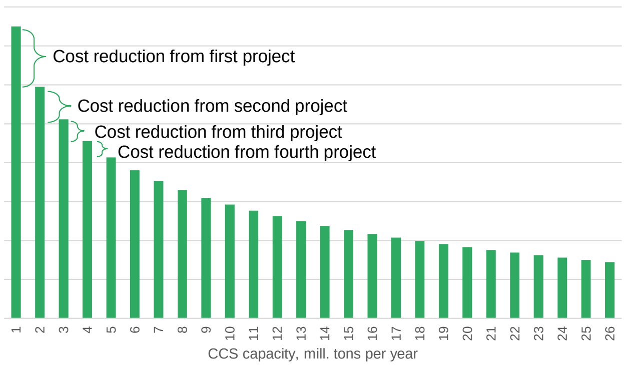


Figure 54- Cost curve of CCS (EUR 200/tonne start rate, 10% decrease of each doubling of capacity)



For projects with capacity of 1 million tonnes of capture per year, one can construct a discrete cost curve. The capacity doubles between 1 and 2 million, then between 2 and 4, and so on. The costs fall quickly initially, then tapers off as more capacity is needed for each doubling.

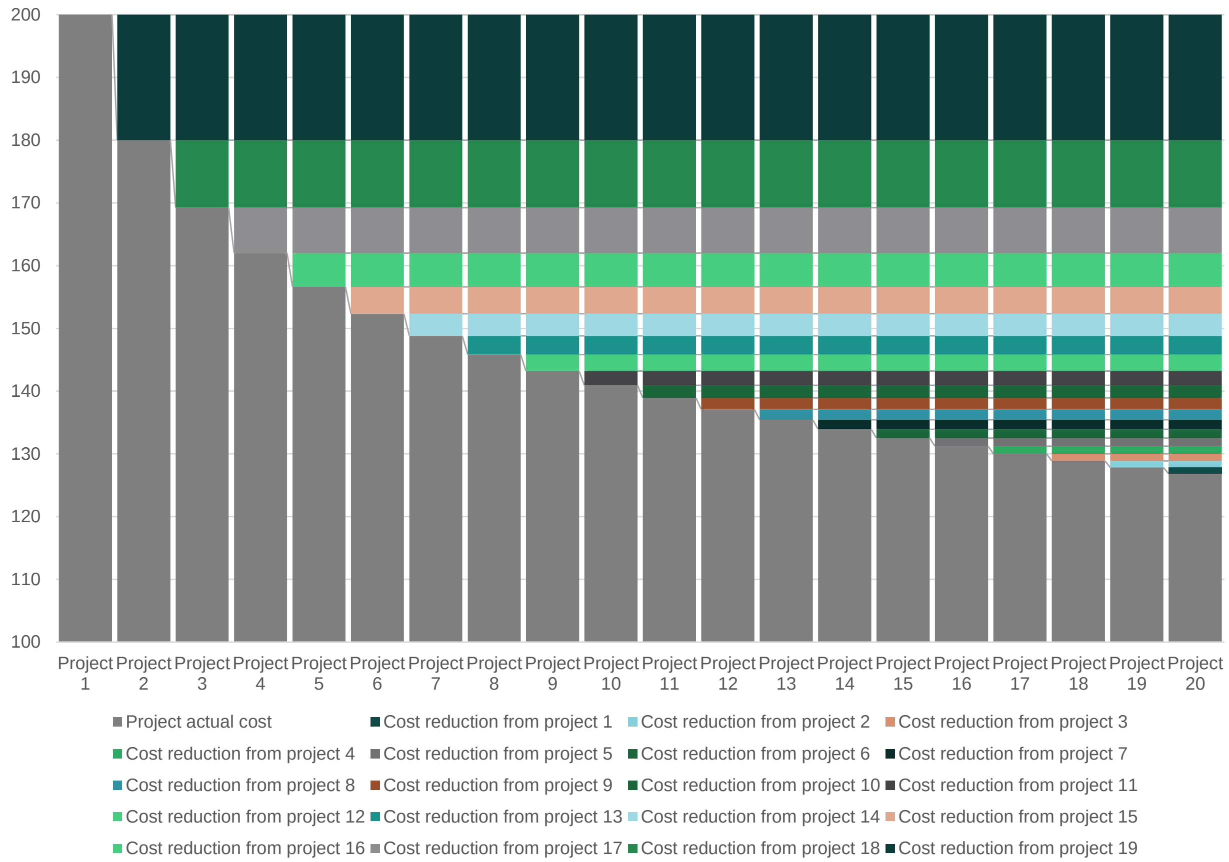
Figure 55- Discrete cost curve for 1-25 Mt capacity (10% decrease per doubling of capacity)



By the nature of the cost curve, which decreases by 10% for each doubling of capacity, the largest cost reductions are associated with the first project and are reduced more gradually as more and more projects are constructed.

We consider the absolute cost reduction, as specified by the cost curve, from each project. The first project contributes equally to cost reductions in future projects, such the contribution is both dependent on its initial contribution as well as the number of future projects. By the nature of the cost curve, early projects contribute most to cost reductions, both by the number of projects and by the high cost reductions initially.

The approach is illustrated in the figure below: Each project contributes to a cost reduction for future projects as specified by the cost curve. The cost reduction per tonne is constant, and the total cost reductions attributed to each project is dependent on how many projects (and therefore tonnes) which are benefitting from the cost reduction.



For the purpose of this project, we take into account EU-wide cost reductions, i.e. that all future cost reductions from the Norwegian full-scale project are counted. The actual benefits are dependent on the number of CCS projects which are actually constructed, and their capacity.

The early-mover projects have higher abatement costs, but their contribution to cost reductions which benefit all future projects, is more important. Since the initial abatement costs are higher than the alternative cost of emissions and the company specific strategic value, the investments are not directly profitable and are unlikely to be undertaken from a purely financial perspective. Without state intervention, investments in CCS projects are not expected to materialize until the costs of emissions are high enough to justify the first-mover projects.

DNV GL has in a study for the full-scale project investigated the cost curve for CCS, based on empirical learning rates in other industries, and the expected developments in the CCS value chain. The cost curve was estimated to have a 10% decrease of costs for every doubling of CCS capacity in million tonnes per year.

Full-scale project contribution to future CCS cost reduction

A societal perspective values the benefits of cost reductions from the initial projects on future projects. This value is dependent on how many future projects are deployed. Based on the analysis of the recent developments in EU and member state policies in chapters 2, 3 and 4, we have assessed minimum and policy-dependent EU pathways. These pathways are used to assess the benefit of the Norwegian full-scale project on cost reductions due to learning from deployment.[222]

To evaluate the cost reduction effect of the Norwegian full-scale project, we must also determine where on the cost curve it lies, i.e. which project it would represent. Based on the global project overview of existing and future large scale CCS projects from the Global CCS Institute and a conservative assumption that all planned large scale CCS projects on industry and power/heat will be realised on schedule, the Norwegian full-scale project could represent a CCS capacity increase from a capacity of 32.5 $MtCO_2$ per year in the world. Assuming cost reductions of 10% per doubling of capacity, an increase from 32.5 to 33.3 MtCO2 would represent cost reductions of 0.22% per tonne, for all subsequent projects, compared to the cost of the first CCS project, or 0.38% compared to the abatement cost of the Norwegian full-scale project. If the first project is assumed to have an abatement cost of 200 EUR/t, the Norwegian project would have an abatement cost of 117 EUR/t, and contribute to future cost reductions of 0.44 EUR/t. While this may appear only a minor reduction, it is assumed that all subsequent projects would benefit from this incremental cost reduction. With an annual capture volume of 1 $MtCO_2$/y, this would reduce annual costs by 440 000 EUR for each additional project, every year over a lifetime of 25 years. In the minimum pathway of CCS in EU28 with 90 $MtCO_2$ captured per year in 2050, with accumulated capture and storage of about 2.2 $GtCO_2$, the net present value of these cost reductions would be EUR 330 million. Higher CCS volumes would be associated with higher values.

[222] It is important to note, that only the future EU28 deployment pathways are assessed here. The benefits to future CCS projects outside the EU are not taken into account here.