A Vision for Carbon Capture, Utilisation and Storage in the EU

Prepared for the European Union's CCUS Forum by the
CCUS Vision Working Group

May 2023

Summary for policymakers

Modelling and reports from a wide range of governments and agencies, including the European Commission ('Commission'), the IPCC, and the IEA, as well as industry and academia, consistently determine that **without large-scale carbon capture, utilisation and storage ('CCUS'), the EU will significantly fail to meet its Green Deal objective of being climate neutral by 2050.**

The EU will need to deploy CCUS at scale for the following reasons:

- **Climate modelling is clear that permanent removal of CO_2 from the atmosphere will become essential,** both to balance any residual 'hard-to-abate' greenhouse gas emissions at net zero, and to reverse the legacy of historic emissions. The geological storage of CO_2 derived from either direct air capture (DACS) or bioenergy processes (BECCS) offers a means of permanently removing large volumes of carbon from the atmosphere – known as carbon dioxide removal (CDR). According to modelling by the Commission and the IPCC, in order to meet its climate objectives, the EU will need to capture and store at least 150 Mt/year of CO_2 of atmospheric or biogenic origin by 2050.
- **CCUS offers a vital means of mitigating emissions from hard-to-abate process industries**, such as cement, steel, chemical production, and waste incineration. For cement, lime, some chemicals, and waste incineration, CO_2 is emitted as an inevitable part of the process rather than from fossil fuel combustion; unavoidable process emissions from cement and lime account for nearly 3% of the EU's total CO_2 emissions. Most heavy industries also rely on fossil fuel combustion to deliver high-temperature heat for a range of processes. While electrification or the use of alternative fuels may eventually be an option for some, CCUS is a key part of the lowest-cost decarbonisation pathway for many emitters, and has the potential to deliver greenhouse gas cuts at scale in the short to medium term. In 2021, total emissions from heavy industry and waste management accounted for around a quarter of the EU's CO_2 emissions.
- **In the power sector, renewable sources are expected to decarbonise the overwhelming majority of the EU power supply by 2050,** but forms of long-term energy storage or low-carbon dispatchable power generation will also be needed to support intermittent wind and solar generation. Particularly in regions with significant existing and recently built fossil power capacity, the application of CCUS to fossil or biomass-fired power plants may enable faster and more complete decarbonisation of the grid.
- **The role of low-carbon hydrogen** (produced from natural gas and permanently storing the resultant CO_2) in the EU remains to be determined. As and when natural gas prices come down, it offers a potentially highly competitive option for low-carbon hydrogen supply. As it is uncertain whether the EU will be physically able to produce all the renewable electricity that it will need for its direct electrification requirements as well as renewable hydrogen by 2050 (and whether sufficient hydrogen imports will be available), low-carbon hydrogen may need to play an

important role in the EU's decarbonisation strategy at least during the transition period.

- **Carbon will remain an essential feedstock for many chemicals and some fuels**, and will need to be sourced from fossil fuel alternatives in a net-zero Europe. Given the limited availability of environmentally beneficial biogenic carbon, the conversion of atmospheric or waste biogenic CO_2 to chemicals and fuels (carbon capture and utilisation) will have a key role to play The conversion of CO_2 to some products can also act as a form of storage, if it becomes permanently chemically bound in the material. This may, for example, be a positive option for certain isolated industrial plants that cannot be competitively connected to a storage grid.

For all these reasons, and based on the compelling evidence from energy system modelling, this working group reaches the conclusion – 'no CCUS, no net zero'. The scale of the challenge is significant. Based on major energy system modelling studies by the European Commission, the IEA, and others, the EU will need to capture and utilise or store between 300 and 640 Mt of CO_2 per year by 2050 to meet its climate goals, with most estimates towards the upper range. Several studies of 1.5°C compatible scenarios indicate that up to half of the CO_2 stored in 2050 will be for the purposes of carbon dioxide removal.

Looking beyond the EU, the challenge is immense: the IPCC's 6th Assessment Report indicates that a median of 665 Gt of CO_2 will need to be captured and stored globally by 2100 to meet a 1.5°C compatible scenario. Not least, the EU needs to lead the way to demonstrate and mature these technologies so that they are ready for global rollout. To show leadership, it is pivotal that clear timelines with appropriately ambitious milestones are set.

However, despite this pressing need to deploy CCUS and build out a CO_2 transport network and storage capacity, the EU has taken very limited action, certainly compared to the focus that it has given to renewable electricity and hydrogen. Compared to the US, Canada, and the UK, it has been slow to prioritise and develop the CCUS industry. Although Norway and some Member States, including inter alia the Netherlands, Denmark and Sweden, have begun to take positive steps to support and plan CCUS projects and infrastructure, greater action is required at the EU and Member State level.

Actions to address the challenge

In its Communication on Sustainable Carbon Cycles, the Commission already targets 5 Mt of 'negative emissions' provided by technologies such as DACS or BECCS by 2030. This will need to ramp up quickly towards 2040, with CO_2 removals in the order of hundreds of Mt likely required by 2050. Without the rapid rollout of a CO_2 transport and storage network, this will not be possible. The Communication also proposed that by 2030 at least 20% of the carbon used in products should come from sustainable non-fossil sources, which is unlikely to be met under current conditions. In finalising the relevant legislative framework, the EU will need to determine the appropriate role that the capture and use of fossil carbon from industrial sources can play as a transitional measure.

Under the currently proposed reform of the Emissions Trading System ('ETS'), in combination with the Carbon Border Adjustment Mechanism ('CBAM'), emitting energy intensive industries will progressively be fully exposed to the ETS over the next few years, via the elimination of free allowances. In the absence of ready access to cost-effective CO_2 transport and storage, many companies will have no reasonable option to decarbonise, and will simply have to purchase ETS allowances, thus increasing costs with no climate benefit and weakening companies' financial capability to decarbonise. For these companies, the availability of cost-effective CO_2 infrastructure during the current decade will be essential to remain competitive and at the same time decarbonise. Without such actions, delocalisation of these industries may result outside the EU, negatively impacting the economy and potentially increasing global emissions.

To meet the EU's decarbonisation needs, especially for energy intensive industry, the first stage of a functioning and cost-effective grid, connecting the industrial 'clusters' where energy intensive industry is concentrated, will therefore be needed by the latter half of this decade when the ETS reforms start to bite, and will then need to be completed in the next decade. Equally, efforts will need to be made to decarbonise balancing electricity in the next decade, for which CCUS-equipped power plants provide an option.

Whilst the ETS is the principal underlying mechanism to determine whether and how much CCUS will be relied upon (compared to hydrogen or direct electrification), there are a number of reasons why a positive approach of the Commission and Member States to developing CCUS will be essential in the coming years.

First, emitting industries have neither the expertise nor ability to develop 'their own' CO_2 infrastructure and storage. This is partly because they are not infrastructure companies, and second, because by its very nature, in order to be cost-effective, grids and storage need to be shared assets. Like gas and hydrogen grids, therefore, they need to be built by infrastructure companies (such as natural gas transmission system and storage operators/owners) to serve multiple customers. Such an approach will enable the emergence of a cost-effective grid used by multiple companies and ensuring economies of scale.

Second, as with hydrogen grids, a 'chicken and egg' problem exists. It is impossible to know at present exactly how much and when demand for CO_2 transport and storage will develop. Modelling can give a good estimate, but by its very nature it will be uncertain. It is not possible to wait until the demand develops to build the pipelines and storage required. In the beginning, the infrastructure will need to be built to cover both current and future demand, thereby harnessing economies of scale, based on a progressive approach of connecting the most important emitting clusters first. The timelines for building such infrastructure are long (for example, Norway's Northern Lights CO_2 storage project will take four years from final investment decision to first storage, and seven years from its first conception).

Third, the investments required are multiple billions of euros. Without a clear and consistent message from the Commission that CCUS is needed and supported, investments will not flow.

It is therefore vital that the Commission now takes the lead in driving forward the development of an EU CO_2 grid and storage capacity compatible with its climate ambition, as a matter of urgency. In addition, action to catalyse the development of markets for qualified, climate-beneficial CCU products will be important. Without such leadership, there is every indication that the necessary infrastructure will not develop, or will develop too slowly and be too small to enable the EU to meet its 2030 and subsequent 2040 target, and to reach full decarbonisation by 2050.

The Commission's leadership on developing the EU's successful renewable energy industry, and more recently its Hydrogen Strategy, point the way forward. The latter catalysed action by Member States and industry, and made a step-change to the development of hydrogen in Europe. The same level of action and commitment is now required for CCUS.

The Working Group therefore suggests that a Commission CCUS Strategy and programme of action, inspired by the success of its Hydrogen Strategy, is now urgently needed. Such a Strategy could include the following key actions (additional details figure in the full report):

- Clear communication of the essential role, scope, and requirements for CCS, CCU, and associated forms of CDR in achieving Europe's climate goals – 'no CCUS, no net zero'.
- Setting targets for the EU and its Member States in terms of storage capacity, transport infrastructure and amounts stored or utilised up to 2050. In particular if – as for hydrogen – such targets would be endorsed by the Council and Parliament, they would provide industry with an important level of security to promote investment and catalyse action at Member State level. Targets should be based on rigorous analysis of viable decarbonisation pathways and likely residual emissions. Based on existing Commission Impact Assessments and modelling, together with other leading studies, we tentatively propose the following targets for consideration:
  - **By 2030:** Total annual storage capacity in the EEA should be a minimum of 80 Mt of CO_2, centred mainly in the North Sea, but with several other key storage regions developing. An initial CO_2 grid is developed connecting major industrial emitting 'hubs' and many more dispersed emitters, notably enabling decarbonisation of important parts of the EU's energy intensive industry that will need CCUS and removals.
  - **By 2040:** All major industrial sources in Europe should have access to CO_2 transport and storage. Total storage capacity in the region should reach at least 300 Mt/year and permanent storage of atmospheric or biogenic CO_2 should reach at least 100 Mt.
  - **By 2050:** Total annual storage capacity will reach at least 500 Mt/year. Capture of atmospheric and biogenic CO_2 will need to provide approximately 200 Mt/year of permanent removals and replace fossil carbon feedstock.
- Requiring Member States to clearly declare the planned role of CCUS in the next revision of their National Energy and Climate Action Plans and long-term climate strategies, identifying domestic capture, transport, use and storage development or CO_2 export objectives, and concrete measures to achieve them. Currently, only three Member States (Denmark, the Netherlands, and Sweden), have made dedicated strategies and funding commitments for the deployment of the technology at large scale by 2030.
- Catalysing a greater and more predictable train of funding at both EU and national level, for example, under the ETS Innovation Fund and, with respect to infrastructure, the Connecting Europe Facility. This should cover both R&D&I (where the EU risks falling behind the US and others) and, as with hydrogen, launching EU and Member State-level carbon contracts

for difference or other appropriate tools to de-risk activities along the CCUS value chain and support the early stages of large-scale deployment in both reductions and removals (beyond first-of-a-kind demonstration).

- Catalysing the creation of a detailed 'atlas' of CO_2 storage resources by 2024 and pre-commercial appraisal funding for strategic storage sites.
- Encourage Member States to put into place the funding and risk-sharing mechanisms (such as grants and guarantees) necessary to ensure the development of CO_2 transport and storage in time to meet industrial and climate needs. Whilst the network can be expected to be fully self-financing in the medium term, some financial support and guarantees will be needed in the early stages of the grid development.
- In this context, lead the development of a CCUS Important Project of Common European Interest (IPCEI) Framework, based on the successful models established for microelectronics, batteries and hydrogen. This could play a similar important 'accelerator' role with respect to CCUS.
- Committing to establish a predictable and transparent regulatory framework for the EU's future CO_2 transport infrastructure through new legislation based on the approach for hydrogen, but in a manner that takes into account the specific nature of CCUS, promotes investment, and ensures third-party access and technical harmonisation where needed.
- Catalysing the rapid development of an 'EU/EEA CO_2 Network Plan' by the end of 2023, with clear transport and storage plans for 2030, 2040 and 2050. While much of the EU's future CO_2 network will be made-up of new and repurposed pipelines, additional transport by road, rail, and ship will also be essential, and storage sites will be owned by a number of different actors. The development of the Network Plan will thus need to be developed by a wide consortium of companies. This should lead to a Ten-Year Network Development Plan for CO_2 infrastructure and the establishment of a CCUS 'ENTSO' by 2024.
- Ensuring a positive climate impact from the conversion of CO_2 to products and materials through application of a consistent and rigorous life cycle analysis, a climate-focused approach to a circular carbon economy, and a clear strategy to transition from the use of fossil CO_2 to atmospheric and biogenic CO_2 for non-permanent applications (such as fuels), as low-carbon energy becomes more abundant.
- Long-term, market-based and regulatory drivers for CCUS both as a tool for industrial decarbonisation and CO_2 removals should be developed. Demand for low-carbon products of heavy industry or qualifying CCU processes can be stimulated by public procurement and carbon-intensity requirements on end-use sectors. A compliance market for permanent and measurable CO_2 removals should also be established, without compromising efforts to reduce emissions; this may be linked to sectoral or national targets based on expected residual greenhouse gases at net zero. A broad assessment of other possible long-term regulatory incentives for adequate CCUS deployment should be conducted.
- Launching forums and platforms for greater knowledge sharing and collaboration between Member States, relevant authorities, and industry, including CCUS Forum working groups and an EU CCUS partnership (or Alliance) reflecting the recommendations made by the WG Industrial Partnership. The deployment of a CO_2 transport and storage network, as well as development of new technologies and a wider societal understanding of CCUS will involve the interaction and coordination of numerous different actors. In this regard, there is considerable scope for sharing the lessons of first-mover Member States with new regions.

Conclusion

Action by the Commission is urgent if the EU is to have a CCUS industry that is 'fit for purpose'. Without such action, it is difficult to see how the EU will be able to meet its climate goals. There is an essential role for the Commission to play in coordinating and accelerating the recent efforts of Member States – which will necessarily take place on a cross-border basis – while also ensuring that no Member State or region is left behind in their efforts to decarbonise using CCUS technologies. Without this leadership, CO_2 capture, transport, utilisation and storage is unlikely to develop sufficiently quickly and at the required scale, and industries will not be able to deliver in accordance with the European Green Deal. To this end, this Vision paper provides a first step and set of recommendations towards a comprehensive CCUS Strategy for the EU.

Definitions

CCS: Carbon capture and storage refers to the capture (separation) of carbon dioxide (CO_2) from various sources, followed by its transport and injection into a suitable underground geological formation for the purposes of permanent storage. While some literature limits the term to CO_2 from point sources for emissions abatement, this paper uses a broader technology-oriented definition to include CO_2 of atmospheric and biogenic origin.

CCUS: Carbon capture, utilisation and storage encompasses the suite of technologies used to capture, transport, utilise, and store CO_2, including CCU, CCS, BECCS, and DACS, for the distinct purposes of emissions reduction or CO_2 removal from the atmosphere.

CDR: Carbon dioxide removal refers to anthropogenic processes which remove CO_2 from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products.

CO_2 Storage Directive meaning “Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance)”.

CCU: Carbon capture and utilisation is a process in which CO_2 is separated from CO_2 point sources or ambient air and is subsequently used in or as a product. In this paper, the term does not include enhanced oil recovery.

BECCS: Bioenergy with carbon capture and storage refers to the combustion or conversion of biomass with carbon capture and storage applied to the resulting biogenic CO_2. BECCS is a CO_2 removal technology, provided the biomass is sustainably sourced and value chain emissions are accounted for.

CEF: Connecting Europe Facility.

DAC: Direct air capture is the separation of CO_2 from ambient air for the purpose of conversion or storage.

DACS: Direct air capture and storage is the separation of CO_2 from ambient air followed by permanent geological storage. DACS is a CO_2 removal technology provided value chain emissions are accounted for.

EEA: European Economic Area.

IAM: Integrated assessment model.

PCI: Project of Common Interest.

PMI: Project of Mutual Interest.

TEN-E: Trans-European Networks for Energy.

TEN-T: Trans-European Transport Network.

Technology-based removals: Encompasses DACS and BECCS. Also known variously as industrial removals, technical removals, and CCS-based removals.

TRL: technology readiness level.

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SECTION 1

Introduction and Scope

The findings of the International Panel on Climate Change (IPCC) have made clear that a rapid, global transition to net zero greenhouse gas emissions will be necessary to limit global warming to 1.5°C above pre-industrial levels and avoid irreversible damage to our climate and society. In response to the urgency of the climate crisis, the European Union (EU) has set a legally binding target of achieving 'net zero' greenhouse gas emissions by 2050,[1] as well as an interim target of a 55% reduction by 2030.[2] Several Member States[3] have implemented their own legally binding plans to reach climate neutrality even faster.

Alongside a range of other carbon abatement technologies, including renewable energy, efficiency improvements, and zero-carbon fuels, carbon capture, utilisation and storage (CCUS) is expected to play a key role in realising both global and EU ambitions to reach net zero within this short time frame. CCUS encompasses a suite of processes involved in separating CO_2 either from emissions sources or the air (capture), followed by permanent storage[4] in deep geological formations (storage) or conversion to products (utilisation).[5]

Owing to the wide variety of decarbonised services these technologies can provide to society, energy system modelling consistently indicates that CCUS will be essential in achieving net zero within the necessary timeframe and at lowest overall cost (Table 1). The European Commission's modelling of scenarios consistent with 1.5°C of warming indicate that between 280 and 600 million tonnes (Mt) of annual

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[1] Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality 'European Climate Law'.

[2] COM (EU) (2019) 640, *'The European Green Deal'.*

[3] Member States include EFTA States where applicable

[4] CO_2 stored in appropriately characterised geological reservoirs is considered to have an extremely low likelihood of ever reaching the atmosphere. Directive 2009/31/EC on the geological storage of carbon dioxide provides a regulatory framework for adequately demonstrating the permanence of storage.

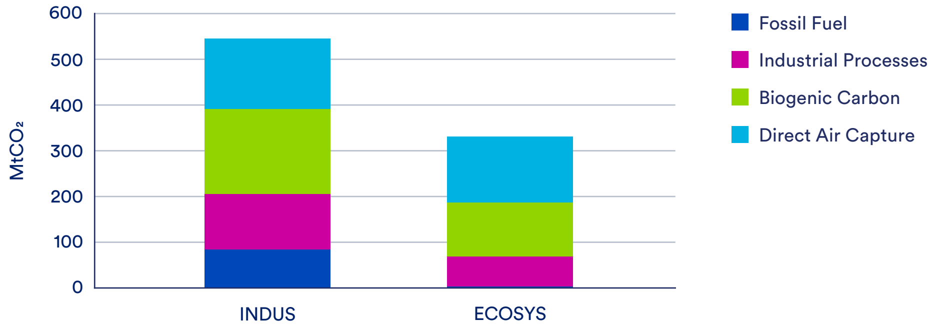
[5] In this paper, CCUS includes the capture of CO_2 from the air through processes known collectively as direct air capture, while recognising that some definitions of CCS and CCUS are restricted to point sources.

CO_2 capture, utilisation, and storage will be required within the EU by 2050[6] (**Table 1, Figure 1**). This is broadly consistent with other assessments such as the IEA's 'Net zero by 2050' scenario, which includes 7.6 Gt of CO_2 captured per year globally by 2050 (of which roughly 350 Mt/year is in Europe) or DNV's 'Pathway to Net Zero', which features over 570 Mt of CCS in Europe by 2050. Of the Integrated Assessment Models (IAMs) presented in the IPCC's 6th Assessment Report, there is a median 665 Gt of CO_2 captured and stored globally by 2100 across 1.5°C compatible scenarios and,[7] of seven 'Illustrative Mitigation Pathways', the only pathway without CCS deployment also requires a nearly 50% drop in global primary energy consumption by 2045.

Table 1: Estimates of CO_2 Capture Required in Europe by 2050 (Globally, Around 36.6 Mt/y is Currently Captured)

	A clean planet for all (EC, 2018)[8]	Sustainable Carbon Cycles (EC, 2021)[9]	Net Zero by 2050 (IEA, 2020)[6]	Pathway to Net Zero (DNV, 2021)[10]	AR6 median across 1.5°C Pathways (IPCC, 2022)[7]
Total CO_2 captured in 2050 (Mt/y)	606 (1.5Tech) 281 (1.5Life)	550 (INDUS) 330 (ECOSYS)	7600 (Global) ~350 (Europe)	568 (Europe)	637 (Europe)
Total capture from biomass in 2050 (Mt/y)	276 (1.5Tech) 84 (1.5Life)	~195 (INDUS) ~115 (ECOSYS)	1380 (Global, 94% stored)	345 (Europe, BECCS only)	0[11]
Total direct air capture in 2050 (Mt/y)	210 (1.5Tech) 123 (1.5Life)	~150 (INDUS) ~150 (ECOSYS)	985 (Global, 64% stored)	194 (Europe, DAC to storage)	19.9
Total DAC or biogenic CO_2 to fuels in 2050 (Mt/y)	227 (1.5Tech) 154 (1.5Life)	~190 (INDUS) ~190 (ECOSYS)	500 (Global)	Not stated	Not stated

Figure 1: Estimated Annual CO_2 Capture Volumes for the EU in 2050 Under Two Possible Scenarios[9]



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[6] International Energy Agency (2021) *Net Zero by 2050. A roadmap for the global energy sector*

[7] Intergovernmental Panel on Climate Change (2022) *Climate Change 2022: Mitigation of climate change -Working Group III contribution to the IPCC Sixth Assessment Report*

[8] COM (2018) 773, '*A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*'.

[9] COM (2021) 800, *Commission staff working document accompanying the Communication on Sustainable Carbon Cycles.*

[10] DNV (2021) *A pathway to net zero emissions.*

[11] The majority of 1.5°C compatible IPCC scenarios include no DACS in 2050. The maximum deployment is 95 Mt/year.

Applications for CCS

The ability to manage flows of CO_2 and direct them to permanent carbon sinks is a fundamental tool for decarbonisation that can unlock a range of climate benefits (**Figure 2**):

- The geological storage of CO_2 derived from either direct air capture (DACS) or bioenergy processes[12] (BECCS) offers a means of permanently removing large volumes of carbon from the atmosphere, provided the biomass consumed is produced in a climate and environmentally beneficial manner.[13] Climate modelling is clear that these CO_2 removals will be essential, both to balance any residual greenhouse gas emissions at net zero, and to bring atmospheric concentrations to acceptable levels by reversing the legacy of historic emissions. Indeed, modelling of scenarios consistent with 1.5°C indicate that more than half of the CO_2 stored in 2050 could be for the purposes of carbon dioxide removal; the IAMs assessed by the IPCC feature a median of 304 Mt/year of BECCS in Europe by 2050.
- CCS offers an important means of mitigating emissions from 'hard-to-abate' process industries, such as cement, steel, and chemical production, and waste incineration, where CO_2 is often either emitted as a consequence of the process chemistry, or when fuel combustion is used to deliver the high temperatures required. Depending on the nature of the emissions, CCUS may be either the only means of abatement or feature in the lowest-cost decarbonisation pathway. In 2019, industrial emissions accounted for around a quarter of EU CO_2 emissions,[14] and demand for most of these products and services is expected to remain constant or increase.[15]
- In the power sector, renewable sources are expected to decarbonise the majority of the EU power supply by 2050, but forms of long-term energy storage or low-carbon dispatchable power generation will also be needed to support intermittent wind and solar generation. In some regions – particularly those with significant existing and recently built fossil power capacity – the application of CCS to fossil or biomass-fired power plants may enable faster and more complete decarbonisation of the grid.
- By decarbonising the production of hydrogen from fossil fuels, CCS can also help meet the region's targets for transitioning to low-carbon fuels, provided capture rates are maximised and supply chain methane leakages are minimised. As outlined in the EU's Hydrogen Strategy, there is a role for low-carbon hydrogen particularly in the near to medium-term while electrolytic hydrogen production using grid electricity remains carbon intensive.

Figure 2: The Distinct Decarbonisation Services Delivered by CCUS Technologies Depending on the Source of CO_2 and Duration of Storage

Storage Duration	**CO_2 Source**	
	Fossil	Atmospheric/biogenic
Temporary	**Non-permanent CO_2 utilisation:** CO_2 to fuels or short-lived materials. Potential emissions reduction are relative to a counterfactual scenario.	**Replacement of fossil feedstocks** for carbon-dependent fuels, materials, and chemicals.
Permanent	**Emissions abatement:** Storage of CO_2 in geological reservoirs or mineralised products.	**CO_2 removal (CDR):** BECCS, DACS, and other forms of permanent CDR.

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[12] Such as biogas production, biogenic waste incineration, or biomass-fired power (or combined heat and power) plant.

[13] Environmentally and climate beneficial biomass should be produced in a manner that does not compromise biodiversity, food security, and sustainable land use.

[14] Endrava (2022) *CaptureMap;* IEA (2021) *Global energy review 2021.*

[15] Material Economics (2022) *Scaling up Europe.*

Applications of CCU

The conversion of CO_2 to other chemicals and materials can be divided into those applications which lead to permanent isolation of the carbon from the atmosphere, and those which do not. Products which are able to permanently bind the captured CO_2, such as mineralisation in concrete or aggregates, may be regarded as fulfilling a similar climate change mitigation function to geological storage (provided CO_2 is not re-released at end-of-life).[16] CO_2 can also be used as an alternative to fossil carbon feedstock for a range of products, including fertilisers, plastics, and fuels, in which CO_2 is later released. Provided the CO_2 used is of atmospheric or biogenic origin, these technologies can play an important role in enabling the continued availability of these products in a net-zero Europe.[17]

This Working Group recognises that there is inevitably uncertainty about the magnitude and scope of the role that CCS and CCU will play in reaching net zero. While some industrial sectors, such as cement and lime, currently have few alternative decarbonisation options, other sectors have competing technological pathways available, and some sectors may be phased out or dramatically diminished by 2050 as they become obsolete or replaced with innovative zero-carbon processes. However, it is essential to also recognise that the more decarbonising technologies and pathways there are available, the greater the chance of success for this unprecedented societal transition, and the greater the chance of minimising the cumulative emissions before net zero is reached. While it may be possible to devise decarbonisation pathways on a sectoral or regional basis without recourse to CCS or CCU, this does not indicate that the development of these technologies may not be critical to achieving our climate goals. On the contrary, there is overwhelming evidence that the permanent storage of both fossil and atmospheric/biogenic CO_2 will be vital in achieving the EU's legally binding target of net zero greenhouse gas emissions by 2050 and can also make an important contribution to the interim target of a 55% reduction by 2030.

Furthermore, while achieving the target of climate neutrality in the EU by 2050 remains the priority, in the long-term, Europe must play a pivotal role in accelerating the deployment of various climate technologies including CCS and CCU to ensure their availability for other regions of the world as they seek to decouple economic growth from greenhouse gas emissions. Ultimately, the evidence is clear: failure to successfully reach full-scale deployment of CCS and CCU in Europe will be a significant failure for climate action.

This paper aims to outline a long-term vision for how the EU, its Member States, and other stakeholders can ensure that CCUS is developed on schedule to fulfil its decarbonising potential and meet the needs of a climate-neutral Europe. It will outline the EU's vision for CCS and CCU to 2050, proposing targets and policy developments that can create predictability for scaling the component technologies and supporting the pathway towards climate neutrality. The Working Group encourages the European Commission to use the Vision paper as the basis for a forthcoming EU Strategy on CCUS.

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[16] As recognised by the ongoing revision to the ETS Directive.

[17] Kähler F et al. (2021). *Turning off the Tap for Fossil Carbon – Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon;* de Kleijne K et al. (2022) *'Limits to Paris Compatibility of CO2 Capture and Utilization.*

SECTION 2

The Current Landscape for CCUS in the EU

The EU has already taken a number of steps to support the development of CCS and CCU in the region. The CO_2 Storage Directive[18] of 2009 establishes a regulatory framework for the geological storage of CO_2, which has been implemented in all Member States. The inclusion of CO_2 storage (and, under the proposed revision, certain forms of CO_2 utilisation) in the Emissions Trading System, means that ETS-compliant emitters can avoid surrendering allowances by capturing and permanently storing CO_2, providing an economic driver for CCS. A limited level of direct funding for CO_2 capture, utilisation, transport, and storage deployment is also available through mechanisms such as the Recovery and Resilience Facility, the Connecting Europe Facility, and the Innovation Fund. Under the Renewable Energy Directive, CO_2 utilisation is incentivised through the eligibility of CO_2-derived fuels as renewable fuels of non-biological origin (RFNBO) or recycled carbon fuels, and is also recognised under the sector-specific instruments ReFuel EU Aviation and Fuel EU Maritime.

However, with limited carbon price signals and few other financial incentives available, CCUS has progressed slowly in the EU and internationally, often struggling to move beyond ‘first-of-a-kind technology’ demonstration projects or, in some sectors, even to reach this stage.[19] The IEA’s Clean Energy Technology Tracker identifies CCUS in both power and industry as one of several technologies that are ‘not on track’ to reach net zero.[20] Of around 30 commercial-scale CCS projects operating today, only two are located in Europe: Norway’s Sleipner and Snøhvit projects based

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[18] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide.

[19] Page 43 of Global CCS Institute (2021) *The global status of CCS: 2021.*

[20] IEA (2022) *Tracking Clean Energy Progress.*

on the dedicated storage of CO_2 removed during natural gas production.[21] The majority of the other operating projects are driven by the use of CO_2 for enhanced oil recovery in North America.

The EU's New Entrants Reserve 300 (NER 300) programme aimed to fund 12 full-scale demonstration CCS projects in 2009, none of which entered operation. Much of the reason for the failure of these projects lay with the design of the scheme, which relied on funding through the sale of EU ETS allowances, the price of which collapsed and meant the programme's available funds were reduced to €1.5 billion from an expected €9 billion.[22] Furthermore, the wide distribution of the funds (namely, that all EU countries should host at least one and no more than three projects, and that no project could take more than 15% of the total funds), meant that large-scale CCS projects with high upfront costs were not feasible.[23]

Long-term demonstration of safe geological CO_2 storage (including over 25 years of experience in the Norwegian part of the North Sea) and large-scale capture in a wide range of sectors have nevertheless established the technical feasibility of CCS and CCU. The challenge is now to develop the innovation and climate policies that can create a commercial case for widespread deployment of the technology wherever it is required. As a solution whose sole function and societal value is emissions abatement, CCS is fundamentally reliant on such policy-based incentives and/or regulatory drivers. Moreover, CCS faces particular challenges relative to some other climate technologies, including high upfront costs (commensurate with large project scale and significant abatement potential), long project lead times, the need for extensive shared infrastructure and new regulatory frameworks, and uncertainty in future demand due to political and regulatory uncertainty. These challenges have been compounded by a lack of firm political commitment at the EU or Member State level, with CCUS often acknowledged but framed as a 'last resort' climate solution that can be properly addressed at a future date. Although 20 Member States have indicated a role for CCUS in their National Energy and Climate Plans, only three (Denmark, the Netherlands, and Sweden) have made dedicated strategies and funding commitments for the deployment of the technology at large-scale by 2030 (*See Appendix 2 for details of these Member State initiatives*).

A recent wave of industry interest in CCUS as a decarbonisation tool has led to over 60 new capture, utilisation, and storage projects being proposed in Europe since 2019, but only one large-scale CCS project (Norway's 'Longship project'[24]) has taken a positive final investment decision (FID) and is now under construction.[25] The ability for emitters to make tangible plans to develop CO_2 capture has been in large part unlocked by the near-term promise of available 'third party access' storage such as Norway's Northern Lights, which are currently reliant on significant investment from national governments. Although several other geological storage sites are now in the early stages of development, these are only likely to amount to around 30-40 Mt/year of capacity by 2030.[26] Given that hundreds of Mt of CO_2 will need to be captured and sequestered annually in the EU by 2050, this current decade will be a critical period for scaling up CCUS and creating the long-lasting policy and funding frameworks required to ensure that deployment continues beyond the demonstration phase.

Furthermore, with the complete phase out of free allowances under the ETS currently proposed by the Commission for 2035,[27] industrial emitters will likely face significant exposure to high carbon prices in 2030. While this is a key step for driving industrial decarbonisation, without ready access to deep decarbonisation technologies such as CCS, carbon intensive industries in many locations across the EU will be left without a viable option to significantly reduce their greenhouse gas emissions in a cost-effective manner. In this case, a consequence of ETS reform and

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[21] GCCSI (2022) Global status of CCS

[22] Page 117 of Åhman M et.al, (2018) *Demonstrating climate mitigation technologies: An early assessment of the NER 300 programme*.

[23] Ibid.

[24] Longship is a full-value chain CCS project including capture from a cement plant and a waste-to-energy plant, CO_2 transport by ship, and offshore storage

[25] A few large-scale CO_2 capture plants associated with CCU are also operational or under construction, including at AVR's waste-to-energy plant in Duiven, the Netherlands, and Arcelor Mittal's Steelanol project in Ghent, Belgium

[26] Carbon Limits (2022) *The gap between carbon storage development and capture demand.*

[27] Awaiting outcome of trilogues.

Carbon Border Adjustment Mechanism introduction could be to increase the cost of these products for EU citizens and industry (due to the need to pay ETS allowances) without any actual reduction in emissions. As EU climate policies apply equally across the region, there is a need to also coordinate the EU-wide provision of open-access CO_2 infrastructure in order to ensure a level playing field for industry within the single market (*See Section 3.7*).

For technology-based CO_2 removals (DACS and BECCS), the Commission's Communication on Sustainable Carbon Cycles currently proposes a (non-binding) EU-wide target of 5 Mt of CO_2 to be removed in 2030, which is far below both the levels required according to energy system modelling (at least 150 Mt/year at net zero) and the near-term growth potential of these technologies (*See Section 3.7*).

SECTION 3

An EU Strategy for CCUS

In Europe, CCUS must be a truly international endeavour, in which Member States can share their CO_2 storage resources, develop new inter-regional infrastructure, and align their regulatory approaches and technical standards where necessary. CCUS is therefore in need of a comprehensive EU strategy that can address these challenges, outline the likely timeline and scope of deployment, catalyse funding and support, provide clear targets, and optimise infrastructure planning. The political commitment signalled by this strategy would create a more favourable environment for project investment, promoting a positive feedback effect on costs through derisking of project finance and learning-by-doing. Similar commitments and targets for renewable energy – and more recently, hydrogen – in the EU's decarbonisation strategy have helped build industry and investor confidence in these sectors, driving deployment and rapidly bringing technologies down the cost curve.

An EU CCUS strategy would aim to:

- Clearly communicate the role, scope, and requirements for CCS and CCU in achieving Europe's climate goals – providing confidence to project developers and investors, aligning definitions and expectations, and raising awareness of the need for these technologies among other stakeholders.
- Ensure the needs of CCUS are comprehensively considered in forthcoming legislation and revisions of existing legislation.
- Facilitate a coordinated approach for Member State commitments, ensuring their plans for CCS and CCU deployment can be realised through greater cooperation.
- Facilitate the coordinated and optimised development of CO_2 transport and storage infrastructure.
- Provide funding and regulatory drivers for CCUS deployment in a near-term (technology commercialisation) and long-term (market-driven) phase.
- Ensure alignment with existing integrated energy strategies such as the European Industrial Strategy.

The following sections will elaborate on some of the specific actions that the EU, its Member States, and other stakeholders can take to realise these aims.

3.1 Communicating the role of CCUS in European climate policy

As outlined, CCUS is necessary to achieve European climate goals and must therefore be recognised for this role in European climate policy. It is important for the EU to clearly state that CCUS is not an expression of diminished climate ambitions or a delay in the transition from fossil fuels, but offers a faster, more resilient pathway to climate neutrality, particularly through its ability to mitigate CO_2 emissions in the near term and at large scale from process industries and to provide permanent removal of CO_2 from the atmosphere.
By taking a leading role in communicating the role for CCUS in decarbonising Europe, supported by clear scientific evidence, the EU can help both Member State governments and CCUS project developers build awareness and support among stakeholders, which is ultimately essential for technology scale-up and market development. New deployment policies should also be rooted in an open dialogue with civil society, labour unions, industry, and other stakeholders. In order to build trust and support, it is essential that new financial support mechanisms and legislation should promote the development of CCUS as a climate solution that can work in parallel with, rather than reduce, efforts to support energy efficiency, renewable energy, and other sustainable low-carbon technologies. Measures to prioritise and maximise CO_2 abatement could include ensuring support mechanisms and standards require high capture rates (at least 95%) and a focus on technologies that are sufficiently scalable to make an impact in the near term.

The EU and other appropriate stakeholders should take steps to:

- Provide unambiguous, evidence-based messaging on the role of carbon capture, utilisation and storage in reaching net zero and accelerating the decarbonisation of energy-intensive industries.
- Ensure CCUS policy and project development takes place with early and open communication with a broad range of relevant stakeholders.
- Ensure that responsibility and costs for decarbonisation lie ultimately with companies in the industrial sector and fossil fuel value chain, through a progressive shift from subsidy-based mechanisms towards exposure to the ETS and other regulatory incentives
- Maintain a permanent stakeholder network/forum, including a working group of Member State representatives (including relevant non-members such as Norway, Iceland, the UK, and Switzerland).
- Develop an online portal as a public information service, highlighting the need for the technology in reaching net zero, the safety and permanence of geological storage, and showcasing key projects and developments.

3.2 EU-wide policy frameworks for CCUS deployment

Depending on local factors such as geology, availability of clean energy, sources of emissions and political constraints, not all Member States are able to store CO_2 within their jurisdictions, or may not choose to include CCS or CCU as part of their climate strategies. For Member States which have not currently included these technologies in their National Energy and Climate Plans, the EU should ensure that sufficient realistic and deliverable alternatives are included and impact assessments conducted.

For Member States which do intend to rely on CCUS to achieve their climate targets, the EU must help ensure that these technologies constitute a viable, equitable, and open-access solution for all regions and industries. The EU can help keep Member States on track to meet their own deployment ambitions for CCUS in National Climate and Energy Plans, based on projections of likely capture volumes, transport options, and potential storage sites. This would ensure that any emerging shortages in domestic storage (or permanent materials-based sinks) are apparent, and that planned CO_2 export volumes are visible to potential recipient Member States, allowing both parties to plan infrastructure accordingly.

CCS is characterised by a ‘chicken and egg’ problem, in that industry will not invest in carbon capture infrastructure unless it is certain that cost-effective transport and storage capacity will be available in time, and storage developers will not invest unless guaranteed CO_2 streams are available. The Commission can create a coordinated ‘virtuous circle’ of investment by pro-actively driving investment and predictability in CCS and storage development, compatible with the EU’s climate ambition. Equally, given the inevitable lack of certainty over exactly how much and where CCS will be deployed, infrastructure planning and business model development should remain flexible and adaptable to changing requirements.

There are a number of overarching policy and regulatory tools that should be considered to help accelerate and coordinate CCUS deployment across Member States:

- Clear milestone targets (2030, 2040, 2050) for deployment of industrial capture and, separately, technology-based CO_2 removals based on scientifically sound long-term modelling and a climate risk minimisation approach. Such targets could be expressed as Mt of CO_2 stored, available storage capacity (in Mt/year), number of CO_2 capture projects deployed in key sectors, or the creation of low-carbon industrial clusters.
- Require Member States to formally declare the planned role of CCS and CCU for emissions reduction and CO_2 removal in their NECPs and long-term climate strategies, the corresponding requirement for domestic storage development or CO_2 export to other states, and concrete steps to achieve these goals.[28]
- Following the approach developed for hydrogen,[29] establish a robust, predictable and transparent regulatory framework for future CO_2 infrastructure, taking account of the specific characteristics of this emerging industry, avoiding monopoly power and ensuring non-discriminatory, open access to essential infrastructure, while stimulating market competition and expansion.
- Clarify the position of CCS and CCU in relevant forthcoming EU legislation and ensure such legislation and funding is coordinated with Member State initiatives.
- Review and consider additional long-term regulatory tools to ensure net zero is achieved and CO_2 storage developed, such as geological carbon accounting and a carbon takeback obligation that would require fossil fuel producers to match production with a growing percentage of sequestered CO_2.[30] Such 'supply-side' regulatory measures could have the advantage of placing the imperative to act directly on those best equipped to store CO_2, as well as ensuring the decarbonisation of fossil fuels as a backstop to inadequate phase out.

3.3 Creating economic drivers for CCUS projects in the pre-commercial phase

Like most decarbonising technologies, implementing CCUS imposes a cost on emitting facilities, including capital costs and ongoing operating costs for CO_2 capture, as well as the payment of fees to providers of CO_2 transport and storage.[31] The ETS should ultimately provide an adequate investment signal for industrial emitters to internalise these costs, but manufacturing industries are currently shielded from the ETS by the free allowances that are allocated to ensure they remain internationally competitive. Although income from surplus allowances can help monetise CO_2 abatement, this uncertain revenue remains a weaker signal than an imperative to avoid the cost of full carbon price exposure. Moreover, even the record-setting ETS allowance prices of around €100/t seen in 2022 remain too low and too volatile to drive the deployment of CCS in many sectors, particularly for first-mover projects that also need to support infrastructure deployment or pay high fees associated with early, lower-volume infrastructure.[32] Taking into account the carbon price and existing funding schemes, there is a revenue shortfall for currently announced projects which is estimated to amount to a cumulative €10 billion by 2030 (**Figure 3**).[31] Some Member States have proposed or implemented supplemental or 'top-up' carbon taxes, which can provide stronger and more predictable price signals to help drive adoption of carbon abatement technologies; these can be targeted at a sectoral level.[33]

In order to close the financial gap between current carbon prices and the cost of first-of-a-kind CCUS deployment in industry, several Member States have implemented or proposed a form of 'Carbon Contract for Difference' (CCfD) or related mechanisms, in which the State subsidises the difference between a carbon reference price (such as the ETS) and a 'strike price' representing the project's true costs per tonne of CO_2

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[28] The WG recognises the progress made in this respect in the recently updated Guidance to Member States on NECPs.

[29] European Commission (2021) *The EU Hydrogen and decarbonised gas market package*.

[30] Jenkins S et al. (2021) Upstream Decarbonization through a Carbon Takeback Obligation: An Affordable Backstop Climate Policy; Zakkour P D et al. (2021) *Progressive Supply-Side Policy under the Paris Agreement to Enhance Geological Carbon Storage*; Kuijper M et al. (2022) *Feasibility Study Phase 2, Final Report' final report 8*.

[31] For CCU applications, there may be additional costs for material and energy inputs, as well as revenue from product sales.

[32] The ETS also does not act as an incentive for emitters of biogenic CO_2

[33] *Enerdata (2022) Denmark will introduce a corporate carbon tax from 2025*.

Box 1: An Illustrative Roadmap for CCUS in Europe

Technology commercialisation and cluster formation phase – 2025-2032

During this first phase of deployment, low-carbon clusters and associated CO_2 infrastructure should be initiated and developed in the majority of Europe's major industrial zones. These developments will be linked with large-scale storage hubs that are currently beginning to be developed in the North Sea, as well as two to four new storage sites in Southern Europe and Central and Eastern Europe – potentially based around currently nascent developments in the Black Sea, the Adriatic Sea, and South-West France. By 2032, North Sea storage will need to have the capacity to inject in the order of 80 Mt of CO_2 annually. Clusters will use regional onshore pipeline networks, initial larger 'trunk line' pipelines, as well as road, rail, and inland waterways for accessing dispersed industrial emitters on their periphery, and CO_2 shipping terminals for onward export where necessary. In regions with less dense emissions, standalone 'source-to-sink' projects will also be required. This phase of development will be primarily based around industrial decarbonisation, and capture technologies in key sectors (such as cement, waste-to-energy, fossil hydrogen, refinery crackers, and steel production) should be de-risked through deployment to a technically standardised and commercially mature level. Significant CO_2 removals can be derived from capture and storage of existing biogenic emissions in industry and power. Technology and infrastructure deployment will initially rely on significant public funding through mechanisms such as the Innovation Fund, Connecting Europe Facility, and Member State initiatives. However, industrial exposure to the ETS price is expected to increasingly drive projects with access to infrastructure and derisked capture technology.

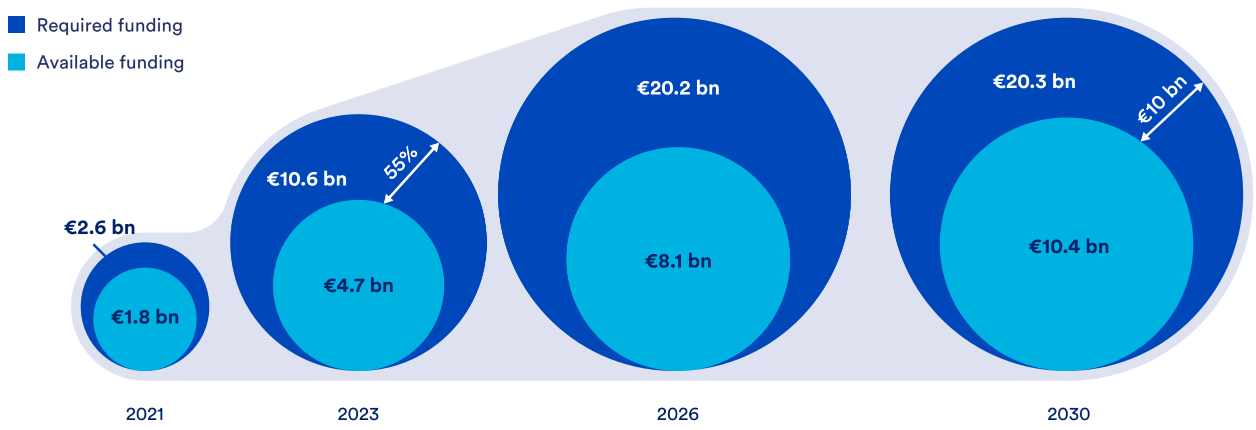
Commercial phase and regional interconnectivity – 2032-2040

This phase will begin to see greater connectivity between industrial clusters, through national and international networks and greater use of long-distance trunk line pipelines. Through these networks and other CO_2 transport modalities (particularly shipping), by 2040, all major industrial sources in Europe should have access to permanent CO_2 storage in geological or material-based sinks. Carbon trunk lines will be established along key transport corridors, enabling economies of scale and connecting major industrial clusters with storage areas. Based on the energy system modelling presented in **Table 1**, total storage capacity in the region should aim to reach at least 300 Mt/year, with roughly half of this likely to be in the North Sea. The full exposure of industrial emitters to the carbon price, together with demand-drivers for low-carbon products, should increasingly provide a business case for industrial decarbonisation through CCUS or other means. In addition, the development of commercial-scale carbon removal projects from DACCS and BECCS will also increase significantly over the decade, driven by new incentives such as compliance markets and the establishment of an ancillary CO_2 removal target within the EU's 2040 climate framework. Based on the studies presented in Table 1, permanent storage of atmospheric or biogenic CO_2 should aim to reach on the order of 100 Mt by the end of this period.

Flexible trans-European infrastructure and growth in CO_2 removal – 2040-2050

In a final decade before reaching carbon neutrality, as unabated fossil carbon emissions diminish there will be marked growth in technology-based CO_2 removals. Provided there is sufficient low-carbon energy availability and biodiversity, food security and sustainable land use are not compromised, modelling suggests that negative emissions from DACS and BECCS may need to reach 200 Mt/year by 2050 (**Table 1**). Atmospheric and biogenic CO_2 will also replace the use of fossil carbon feedstocks for all products and fuels which remain dependent on carbon. To accommodate growth from removals and remaining industrial and power sources, total annual storage capacity of at least 500 Mt/year will be needed. During this period, a highly competitive, harmonised, and flexible regional market for CO_2 transport and storage will need to be well established, in which capture locations have access to a range of possible CO_2 storage sites or offtake for CO_2 utilisation (for atmospheric or biogenic CO_2).

Figure 3: Estimates of the cumulative gap between announced funding for carbon capture and storage and the funding announced projects require to have a positive net present value[34]



abated. Operating on this principle, the Netherlands' SDE++ scheme for decarbonising technologies has included CCUS and enabled the Porthos project (covering four emitters in the Port of Rotterdam) to progress towards a final investment decision in 2022. Similar mechanisms are proposed for funding CCUS and industrial decarbonisation in the UK, Denmark, and Germany, and may also be included under the current revision of the Innovation Fund. This approach has the advantage of providing a predictable, annual revenue to projects over the contract period, while also allowing the total subsidy to decline over time as the carbon price increases. For specific applications of CCS, such as hydrogen production, power generation, and CO_2 removals, other forms of contract for difference-based subsidies have been considered, for instance, based on strike and reference prices for hydrogen and power, or the voluntary market value of removal credits.[35]

The Innovation Fund can be an effective mechanism for stimulating the development of first-of-a-kind CCUS demonstration projects, having already selected eleven CCUS-related projects under its first two calls for large-scale projects. However, experience has shown that new low-carbon technologies require sustained support through several deployment iterations, just as many years of power-price incentives and other mechanisms have supported the maturation of wind and solar energy. Similarly sustained support – from a combination of EU and MS initiatives – will likewise be necessary for developing various applications of CCUS to commercial prospects that can attract large volume, low-risk finance, and be driven by market incentives alone. This will enable the build-up of transport and storage infrastructure and supply chains, and the standardisation of key technologies. The EU should aim to:

- Increase the size and scope of the Innovation Fund available for CCUS support and/or introduce alternative mechanisms to cover projects that deliver significant decarbonisation, considering:
    - Significant optimisation of high TRL technologies;
    - The degree of impact of applications of a demonstrated technology in a new region or sector, for instance, by prioritising sectors with fewer alternatives to CCUS;

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[34] Carbon Limits & Clean Air Task Force (2022) *The gap between carbon capture and storage ambitions and available funding* (based on project announcements as of January 2022 and assuming a carbon price increasing from €60/t to €93/t in 2030).

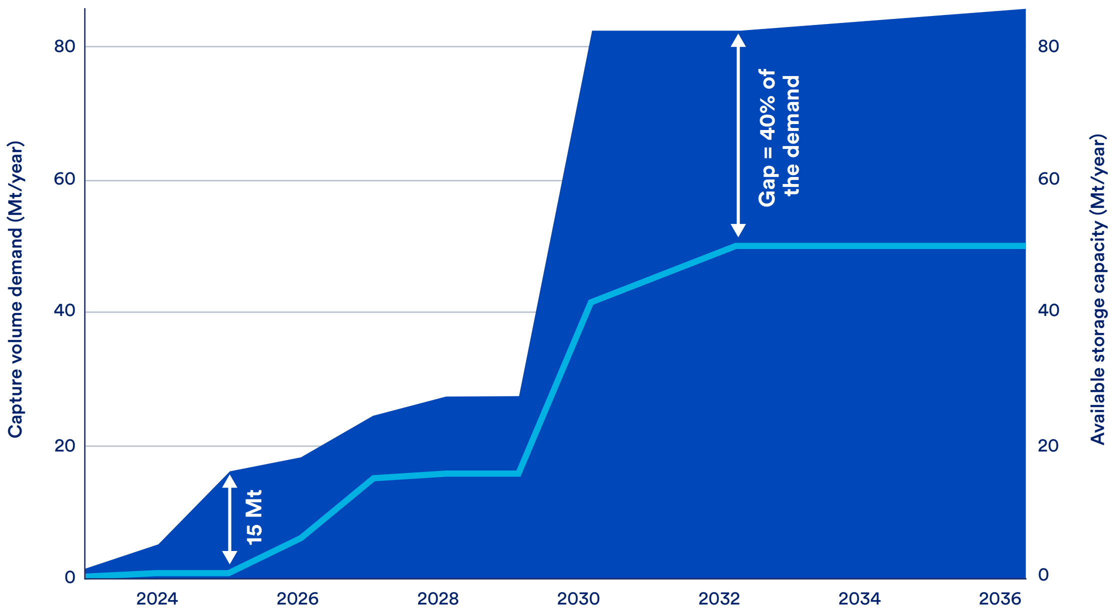
[35] BEIS (2022) *Carbon capture, usage, and storage (CCUS): business models*.

  - Innovation beyond technology – in development of commercial models or supply chains;
  - Frontloading early Innovation Fund calls to maximise earlier emissions reductions and inclusion of CCfD mechanisms within the Innovation Fund.
- Encourage Member States to develop a sustained and predictable stream of funding through mechanisms which provide a bankable revenue stream over a project duration, for example, via a CCfD model. These incentives can help commercialise technologies beyond the demonstration phase to enable rapid transition to a market-driven phase.
- Ensure that carbon capture, utilisation and storage is eligible for new and existing funds for industrial decarbonisation.
- Promote negative emissions (CDR) via DACS and BECCS by developing a European certification system for CO_2 removal and establish new demand incentives to drive near-term and long-term investment in these technologies (*See also Section 3.7*).

3.4 Establishing large-scale storage for all

The promising progress of nationally supported CO_2 transport and storage projects such as Norway's 'Northern Lights' and Denmark's recent announcements has catalysed the recent growth in plans for CO_2 capture projects, however, the development of geological storage sites is falling far behind demand from emitters. With a potential 50% shortfall in developed storage capacity projected by 2030, it is clear that the timely development of storage sites is a critical element in the deployment of CCS in Europe (**Figure 4**). Including the North Sea resources of the UK and Norway, Europe is estimated to possess on the order of hundreds of gigatonnes of theoretical capacity for CO_2 storage,[36] but individual storage sites can take several years to develop,[37] requiring detailed geological assessments and often lengthy permitting processes. Developments can also require

Figure 4: The Widening Gap Between Volumes of CO_2 Captured and Available Storage Sites[38]



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[36] Anthonsen K L, Christensen N P (2021) *'EU geological CO_2 storage summary' Geological Survey of Denmark and Greenland for Clean Air Task Force. Rapport 2021/34*.

[37] ZEP (2014) *Business models for commercial CO_2 transport and storage*.

[38] Carbon Limits & Clean Air Task Force (2022) *The gap between carbon storage development and capture demand* (based on project data as of Jan 2022).

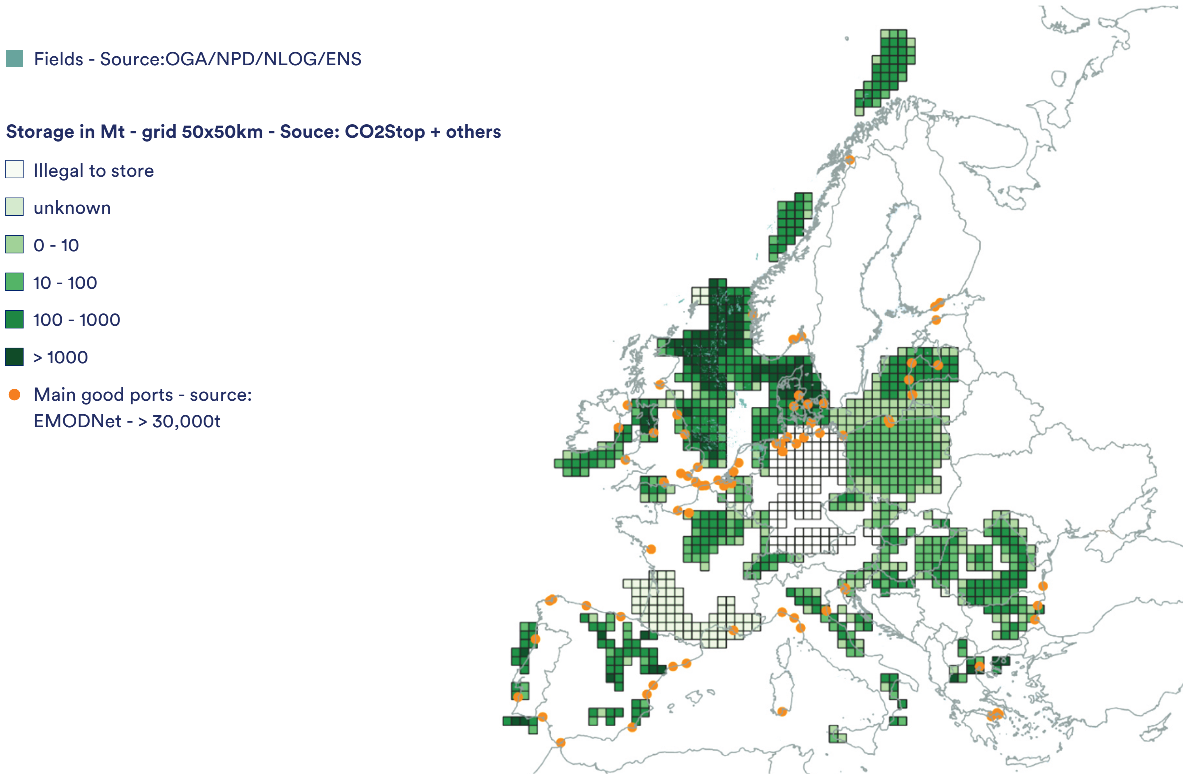
Figure 5: Regional CO_2 Storage Capacity in Europe Based on Current Estimates[39]

significant pre-construction phase investments that carry a financial risk unless there is certainty of demand from CO_2 capture plants and, despite the recent growth in industry interest, this demand remains uncertain while so few Member States have committed significant political backing or funding to CCUS and available CO_2 transport options remain limited.

The selection of several CO_2 capture and storage projects under the first calls of the Innovation Fund has fortuitously been enabled by the availability of state-funded storage sites in the North Sea; these near-term sites are now heavily oversubscribed. In the Netherlands, the success of the SDE++ scheme in driving new CCUS projects stalled in 2021 due to a lack of storage capacity able to meet the schedule of bidding projects. In the initial phase, it is essential that the EU also takes steps to develop storage capacity ahead of demand and break this 'chicken-and-egg' impasse facing many projects. The recent inclusion of CO_2 storage under the TEN-E regulation and the funding of two new storage sites (in Iceland and Bulgaria) under the Innovation Fund are important steps. However, to help guide the market and ensure that capacity is developed in a pre-emptive and coordinated manner, the EU, Member States, relevant competent authorities, and prospective private-sector storage site developers should consider:

- A plan to identify and facilitate the development of strategically placed storage sites, based on Member State submissions of prospective capture and storage volumes.

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[39] Carbon Limits (2021) *Re-Stream: Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe*. Note: Many areas of 'unknown capacity' or no data have been further elucidated by national and regional studies. For example, gas fields in SW France are estimated to have a combined capacity of over 600 Mt of CO_2.

- Providing funding for relevant expert bodies (e.g., geological surveys) to establish an open-access CO_2 storage resource 'atlas' for the whole region, based on consistent methodology and maximising access to data from oil and gas operators.[40]
- Providing dedicated funding (potentially through the Innovation Fund) to characterise and mature large-scale (>100 $MtCO_2$) storage sites in strategic locations to 'injection-ready' status – this could potentially include a tender process to develop target storage capacities by key dates.
- Ensuring that EU or Member State-funded projects with a CO_2 storage component include surplus, third-party access capacity.
- Developing regulatory mechanisms and incentives to ensure the oil and gas industry and other owners of sub-surface data are actively enabling storage site development, including the acquisition and sharing of data, advance indication of plans for depleting fields, and the maintenance of existing oil and gas infrastructure that may have future value for CO_2 activities.
- Providing EU guidelines to streamline storage site permitting (aiming for a maximum of 9 months) and create a platform for knowledge sharing and capacity building between the relevant Member State regulators.
- Investigating new approaches to the financial security requirement for storage sites (such as a portfolio approach) and the creation of an EU-wide insurance fund.
- Creating regional coalitions to ensure the North Sea Basin and other key cross-border European storage reservoirs are developed on schedule to deliver the injection capacities required by 2050.

It is also important to acknowledge that current plans for CO_2 storage development are heavily concentrated in the North Sea, where well-characterised, favourable geology, existing offshore assets, and supportive policy provide a commercial opportunity. However, suitable storage geology is found in most regions of Europe (**Figure 5**), including well-located onshore storage resources in Central and Eastern Europe and offshore

Box 2: U.S. Initiatives to Develop CO_2 Infrastructure

CO_2 capture, transport, and storage has a long history in the USA, owing primarily to the widespread use of CO_2 for enhanced oil recovery. There are around 13 large-scale capture projects operating in the country, over 8000 km of CO_2 pipeline, and widespread suitable geology for CO_2 storage. In 2003, the US Department of Energy (DOE) established seven Regional Carbon Sequestration Partnerships (RCSPs), tasked with determining the best CO_2 storage approaches and locations throughout the country, as well as piloting CO_2 injection. Following on from this work, the DOE launched the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) in 2016, with the aim of furthering the development of storage complexes with the potential to store over 50 Mt of CO_2. With $45 million in funding, this project encompassed project screening, site characterisation, and permitting phases, essentially enabling suitable sites to reach 'injection ready' status.[41] In 2021, the Infrastructure Investment and Jobs Act (IIJA) allocated $12.1 billion across the whole CO_2 value chain, including $2.54 billion for capture demonstration projects and $2.1 billion in low interest loans for shared CO_2 transport infrastructure.[42] In addition, a CO_2 Storage Commercialization Program was established to build on CarbonSAFE, providing $2.5 billion in grant funding for the development of new or expanded CO_2 storage projects and associated transport, including funding for developmental and construction phases. IIJA also supports CO_2 removal technology through the allocation of $3.5 billion for the creation of four 'DAC hubs' that will capture at least 1 Mt/year each. These initiatives to support capture demonstration plants and infrastructure underpins broader efforts to support CCUS under the Inflation Reduction Act (2022), which raised the value of the 45Q tax credit to companies capturing and storing CO_2 to up to $85/t for point sources, and $180/t for DAC.

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[40] See existing CO_2 atlases for Norway, the UK, the Nordic countries, Germany, and Spain.

[41] DOE (2016) CarbonSAFE.

[42] CATF (2022) *Carbon management provisions in the infrastructure investment and jobs act*.

storage in the Black Sea and the Mediterranean. These areas must also be developed to viable sites to ensure that all the EU's emitting industries are able to access decarbonising infrastructure, but many countries face challenges including inadequate or limited implementation of the CCS Directive, a shortage of regulatory or technical capacity, and increased communication challenges associated with onshore storage. Development of CO_2 storage in new regions should be accelerated through sharing of technical and regulatory best practice and experience, capacity building within Member State governments, and EU-coordinated efforts to identify and develop promising storage sites. To this end, recommended actions include:

- Promote capacity building and knowledge sharing initiatives between government and other stakeholders in relevant Member States, particularly in relation to storage site permitting requirements.
- Member States to evaluate and update where necessary their implementation of relevant CO_2 transport and storage regulations, such as the CO_2 Storage Directive.
- Explore ways in which the Just Transition Fund and the Cohesion Fund could coordinate and be used more broadly to help industrialised regions access CO_2 storage.

3.5 CO_2 transport infrastructure for Europe

Creating Clusters and Localised Infrastructure

Most of Europe's current wave of carbon capture projects are based on the premise that the commercial framework for CO_2 capture can be separate from that of transport and storage. Under this model, an emitter would pay to install and operate the CO_2 capture process, and then provide a CO_2 transport or 'transport and storage' entity with a fee to take CO_2 at the plant fence. It is unrealistic to expect that an industrial emitter will be willing, or indeed able, to undertake investments in CO_2 transport and storage, where it has no expertise. In addition to simplifying project structure for emitters, this approach lends itself to the development of shared infrastructure that can achieve economies of scale by processing large volumes of CO_2, while also providing a solution even for small emitters that may not justify new CO_2 infrastructure alone. Heavily industrialised zones or 'clusters', often associated with port areas, are the most promising first movers for establishing this kind of shared CO_2 network, potentially alongside complementary infrastructure for hydrogen and heat (**Figure 6**). A CO_2 network in the Port of Rotterdam (linked to offshore storage) is proposed by the Porthos project, while the Innovation Fund-selected Kairos@C project envisages a similar solution for emitters in Antwerp. In Copenhagen, a network of local waste-to-energy, combined heat and power plants, and other emitters, are planning shared infrastructure under the 'C4' project. Industrial clusters or CO_2 export terminals can also act as collection hubs for emissions from more isolated facilities, such as cement plants, by pipeline, waterways, road, or rail.

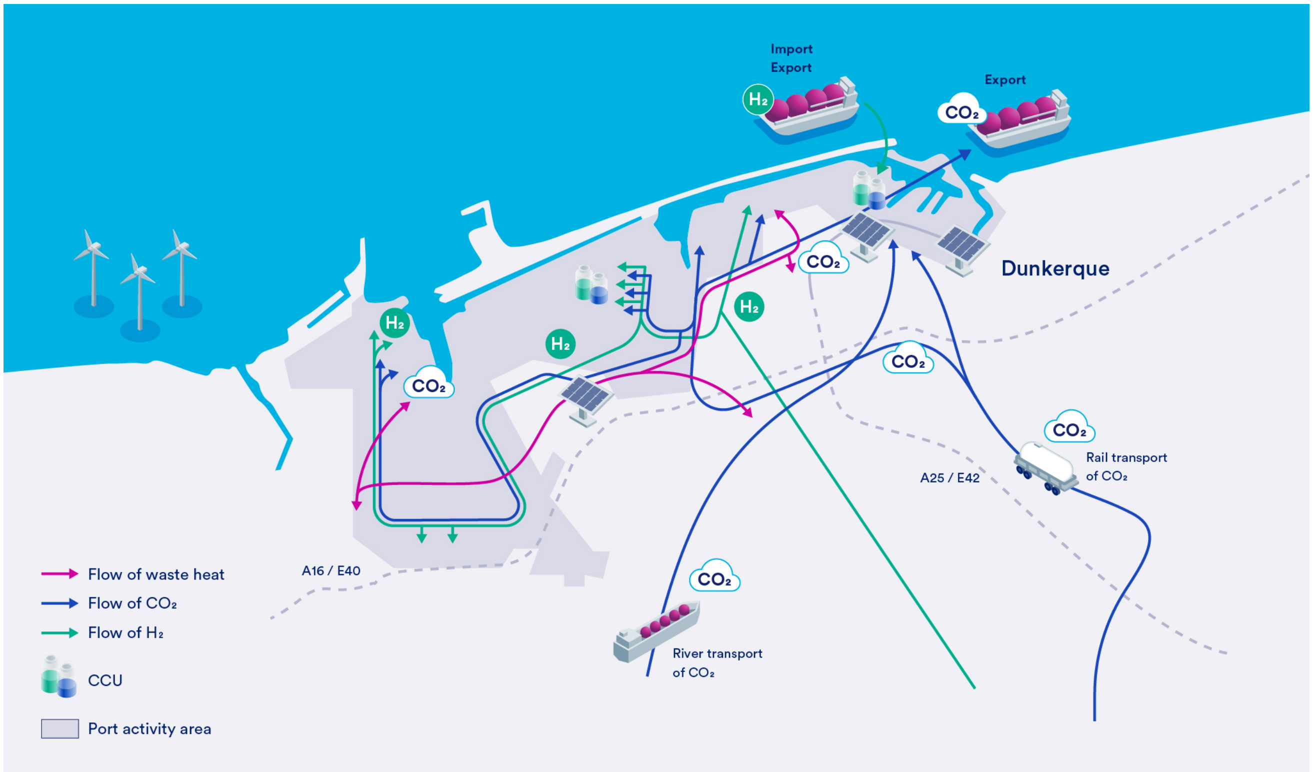
Alongside the scaling opportunities and flexibility offered by CCUS clusters, there are challenges for the design of policy and funding initiatives, which have historically taken a project-by-project approach. Separation of the CO_2 value chain also introduces new project risks, as emitters require assurances that CO_2 offtake will be available and storers (or CO_2 users) require a dependable supply of CO_2. These challenges will diminish as clusters grow in size and alternative offtake options become available, however, in the first phase of development the EU can act to:

- Enable MS and EU funding to use regional synergies and the potential scalability of climate impact as additional criteria for decarbonisation projects, moving beyond project-specific assessment and funding.
- Facilitate the development of risk management strategies and business models which enable the steady expansion of cluster networks.
- Incentivise EU or Member State-funded infrastructure to include some surplus capacity, accessible to third parties.
- Expand the ability of existing infrastructure development tools, including TEN-E, PCIs, TEN-T, and CEF, to support the creation of local CO_2 networks, terminals, and access for dispersed emitters:
- Extend TEN-E support for CO_2 infrastructure beyond PCIs and PMIs.
- Include non-pipeline CO_2 transport modalities in the TEN-T regulation.

Inter-regional and International Transport Networks

Cross-border transport of CO_2 will be integral to all stages of CCUS deployment in Europe and will extend beyond the borders of the EU (**Figure 7**). Several of the most progressed capture and storage projects are based on shipping of CO_2 to collection points associated with offshore storage in the North Sea (or to basalt storage in Iceland). Many planned industrial clusters without direct access to storage within the Member State, such as those at Dunkirk and Antwerp, will rely on shipping

Figure 6: Illustrative Schematic of a Decarbonised Industrial Cluster in the Port of Dunkirk, Including a CO_2 Network, Export Terminal, and Connection to Inland Emitters Through Non-pipeline Transport.[43]



in the first instance, potentially progressing to pipelines in the long-term. In the medium term, wider regional CO_2 networks will be required, giving access to more dispersed emitters and inland clusters further from storage, and forming connections between clusters. In addition to expanding access, larger networks will help reduce costs through economies of scale and reduce project risk by providing CO_2 emitters and offtakers with a wider portfolio of sinks and sources. National CO_2 pipeline networks have already been proposed within Germany and Belgium,[44] while joint ventures for cross-border pipeline development include plans to link Belgium and Germany with the Norwegian continental shelf,[45] and Rotterdam to North-Rhine Westphalia.[46] Although the Commission has indicated that transport for offshore storage between EEA countries should not be formally restricted by the London Protocol,[47] further clarity is required from the International Maritime Organisation and a solution is still required for CO_2 export to the UK.

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[43] Dunkerque Promotion (2021) Dunkerque, territoire d'industrie décarbonée.

[44] OGE (2022) *OGE and TES join forces to develop a 1000-km CO_2 transmission system*; Fluxys (2022) *CO_2: Preparing to build the network*.

[45] Equinor (2022) Fluxys and Equinor launch solution for large-scale decarbonisation in North-Western Europe; Equinor (2022) *Equinor and Wintershall partner up for large-scale CCS value chain in the North Sea.*

[46] Port of Rotterdam (2022) *Broad industry support for Delta Corridor project*.

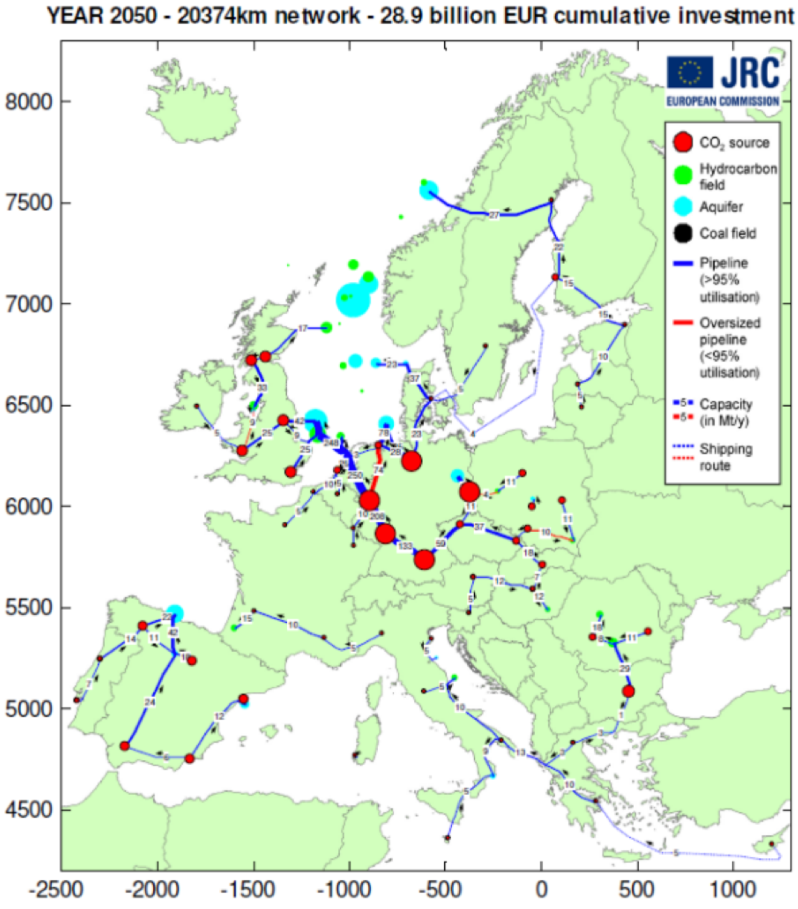
[47] European Commission (2022) *The EU legal framework for cross-border CO_2 transport and storage in the context of the requirements of the London Protocol*

The EU can help guide and derisk the development of an inter-regional CO_2 transport network by identifying the key transport routes and potential trunklines, including potential volumes to be transported. It is vital to ensure that CO_2 networks in each Member State develop in a coordinated and harmonised manner, with shared technical standards for CO_2 specifications and compatible regulatory protocols. Long-term planning of a pan-European CO_2 network will also help early-stage transport options progress towards cost and volume-optimised solutions (such as shared pipelines or large-scale shipping where appropriate), and avoid lock-in of higher cost configurations.

To this end, recommended actions include:

- Develop an overarching roadmap for the development of optimised cross-border CO_2 transport infrastructure including an initial 'no regrets' infrastructure, 'CO_2 backbone' pipelines for Europe, and solutions for dispersed emitters using all transport modes available.
- Establish a 10-year Network Development Plan for CO_2 infrastructure, following the model of gas and electricity networks.
- Establish a Europe-wide regulatory platform for multi-modal CO_2 transport infrastructure, ensuring principles of non-discriminatory, open access.
- Develop a Europe-wide set of technical CO_2 specification standards for transportation and mechanisms for mass and composition tracking.

Figure 7: Illustrative Example of a Potential Trans-European Network for CO_2 Based on Early JRC Modelling[48]



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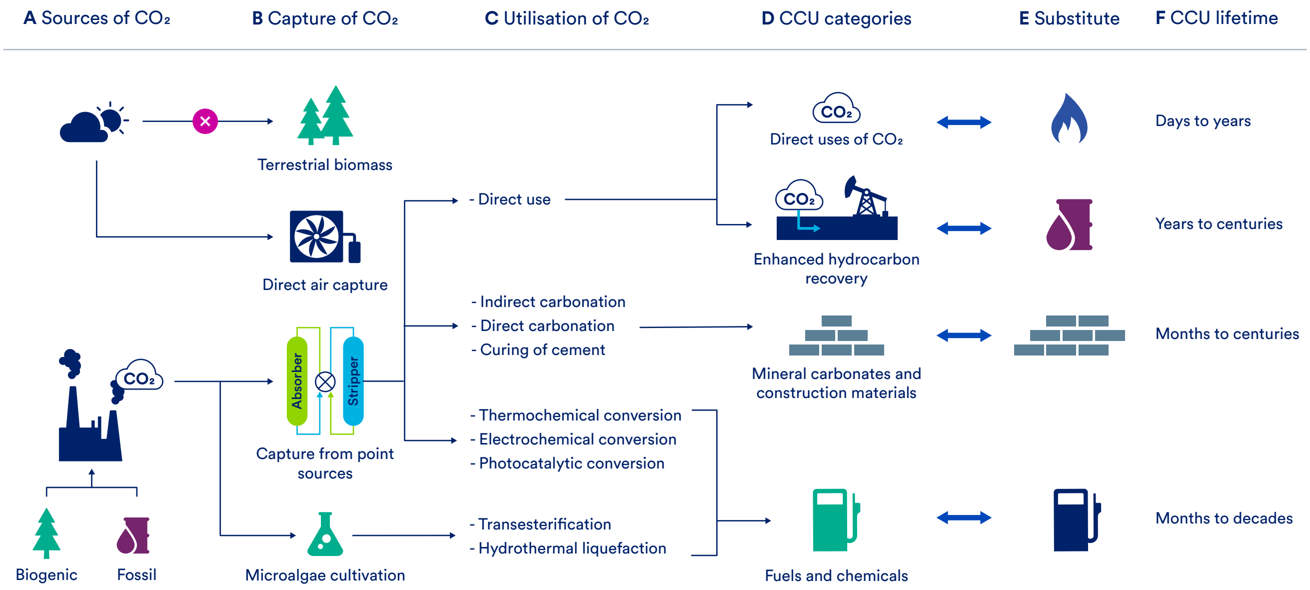
[48] Morbee J et al. (2010) *The evolution of the extent and the investment requirements of a trans-European CO_2 transport network.*

- Establish a new CO_2 infrastructure operator platform (analogous to ENTSO-E and ENTSO-G).
- Ensure a high degree of private sector due diligence, monitoring and regulatory oversight to minimise the possibility of CO_2 leakage.
- Encourage Member States that are party to the London Protocol to ratify the amendments concerning cross-border transport of CO_2.
- Facilitate sharing of best practices and experience from bilateral agreements on cross-border transport and storage of CO_2.
- Provide guidelines on how to collaborate and trade CO_2 with non-EEA countries, and work to include recognition of CO_2 storage in the UK as non-emitted CO_2 under the EU ETS.

3.6 Ensuring a positive climate contribution from CO_2 utilisation

Carbon capture and utilisation (CCU) is a broad term which covers a range of different applications where CO_2 is captured from point sources or ambient air and is subsequently used in or as a product.[49] CCU could contribute to climate change mitigation if it replaces fossil feedstocks, avoids upstream emissions, or isolates CO_2 from the atmosphere over a climate-beneficial time-scale.[50] The extent of the climate change mitigation contribution depends primarily on: a) the source of the CO_2 used (fossil, biogenic, or atmospheric); b) the converted form of the CO_2 and the lifecycle of that product; c) the process and inputs required for the conversion; and d) the counterfactual scenario in the absence of the CO_2-derived product (**Figure 8**).

Figure 8: An Overview of the Scope of CCU[51]



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[49] CCU processes can also be understood to include the conversion of CO_2, where it is emitted as an industrial by-product such as in blast furnace gas

[50] de Kleijne K et al (2022); Kätelhön A et al. (2019) *Climate Change Mitigation Potential of Carbon Capture and Utilization in the Chemical Industry*; Thonemann N and Pizzol M (2019) *Consequential Life Cycle Assessment of Carbon Capture and Utilization Technologies within the Chemical Industry*; Hepburn C et al. (2019) *The Technological and Economic Prospects for CO_2 Utilization and Removal*; Detz R J and van der Zwaan B (2019) *Transitioning towards Negative CO_2 Emissions*.

[51] Page 169 of de Kleijne K et al. (2022) *'Limits to Paris Compatibility of CO_2 Capture and Utilization*.

Some CO_2-derived materials can act as a relatively stable long-term sink for CO_2 and can therefore provide a similar function to geological storage. In particular, this includes the formation of mineral carbonates in concrete or synthetic aggregates for building materials. For example, CO_2 can be used in the place of steam during the curing of concrete, with the result that CO_2 is absorbed and converted to stable carbonates. CO_2 can also be converted to polymers for materials – in this case, CO_2 may ultimately be re-emitted if incinerated without CO_2 capture.

Currently, the EU ETS does not recognise the utilisation of CO_2 as yielding a climate-benefit which can count towards emissions reductions of installations. However, the ongoing revision to the ETS Directive could recognise emissions reductions achieved only where captured CO_2 is permanently chemically bound in a product so that they do not enter the atmosphere under normal use and disposal.[52] Such a step would require an appropriate methodology to define ‘permanently bound’.

Large potential markets may exist for the conversion of CO_2 to fuels, such as synthetic methane, methanol and ethanol, where the CO_2 is re-released when the fuel is used. These processes usually require low-carbon or renewable hydrogen availability for hydrogenation of the CO_2, increasing the overall energy demand. A significant planned project of this type is Holcim’s initiative to convert 1 Mt/year of CO_2 from the Lägerdorf cement plant to synthetic methanol by combining it with renewable hydrogen; this has been selected in the most recent round of the Innovation Fund.[53] The use of fossil CO_2 for synthetic fuels is also currently supported through eligibility to satisfy EU targets for the use of RFNBOs and recycled carbon fuels.[54] In these CCU applications where the fossil CO_2 is ultimately emitted, the abatement potential is determined relative to a counterfactual scenario, in which fossil carbon is used for both the point-source emitter and the fuel application (limiting the abatement over the combined energy system to a maximum of 50%).[55] Provided a net climate benefit is identified, the non-permanent use of fossil CO_2 is preferable to emitting CO_2 in the near term and can also serve to accelerate development of both $CO2_2$ capture and conversion technologies.

However, achieving net-zero emissions will ultimately require a transition to non-fossil carbon feedstocks well before 2050. Provided sufficient quantities of low-carbon electricity are available, the European Commission has identified a potentially significant future role for synthetic fuels based on atmospheric CO_2 obtained from direct air capture, ranging from 154 Mt/year of CO_2 to 227 Mt/year by 2050 across 1.5°C compatible scenarios.[56] When using atmospheric CO_2, the carbon (together with hydrogen) acts as an energy vector that may allow more straight-forward adoption of low-carbon fuels, particularly in sectors such as aviation, where use of non-carbon-based fuels may not be possible. Other potential uses of atmospheric or biogenic carbon in future could be as a replacement for fossil carbon feedstock in a range of carbon-based products such as plastics, fertilisers, and pharmaceuticals, although demand should also be minimised through improvements in material recycling.[57] Given the ongoing need for carbon feedstocks for a range of sectors, efforts should be made to move progressively from the use of fossil CO_2 towards atmospheric and sustainably sourced biogenic CO_2, while ensuring adequate incentives are in place to deliver the necessary levels of DAC deployment and accompanying low-carbon energy sources.

CO_2 conversion activities may also take place for reasons other than climate change mitigation, such as reduced consumption of fossil fuels or other resources as an end in itself; however, processes and projects should also be able to demonstrate a clear climate benefit to be considered within the scope of a forthcoming EU CCUS Strategy. For any CO_2 utilisation technology, it is imperative to

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[52] Directive 2021/0211 (COD) of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757.

[53] Innovation Fund 2nd call for large scale projects – list of proposals pre-selected for a grant.

[54] Delegated Act supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for assessing greenhouse gas emission savings for certain fuels.

[55] IEA (2019) *Putting CO_2 to use*

[56] European Commission COM(2018) 773 *A clean planet for all.*

[57] Kähler F et al. (2021) *Turning off the Tap for Fossil Carbon – Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon*.

assess the emissions abatement potential through a thorough life-cycle analysis, taking into account the carbon intensity of all energy inputs and with careful choice of counterfactual scenario.[58] Industry, the EU, and Member States can work to ensure the fossil CO_2 sources are able to transition as rapidly as possible to abatement through permanent storage (either geologically or in materials), for example, by making CO_2 infrastructure available to all point source emitters. CO_2 for both geological storage and utilisation pathways will share the same transport infrastructure, so the combined potential flows must be considered in planning future infrastructure, particularly within industrial clusters. To ensure CCU technologies make a positive contribution towards the EU's climate goals, the EU should consider:

- Including the use of captured CO_2 in the ETS Directive only in cases where the CO_2 is permanently chemically bound in a product so that they do not enter the atmosphere under normal use and disposal.
- Developing and implementing robust methodologies for life cycle analysis to determine the potential climate impact of CO_2 conversion to products.
- Certification of low-carbon materials to recognise any potential embedded climate benefit associated with CO_2 utilisation.
- Analysis of how much atmospheric or biogenic CO_2 will be required to replace fossil carbon-based products, taking into account future consumption trends and other potential sources such as biomass.
- Establishing regulations and incentives to prioritise the use of environmentally beneficial biogenic and atmospheric CO_2 in those sectors which are most reliant on carbon feedstocks and to establish a trajectory for the transition from fossil to non-fossil carbon sources. Such a framework should also help deliver the goal of the Sustainable Carbon Cycle Communication that 20% of products should be produced from non-fossil carbon by 2030.
- A strategy to ensure that any CCU of fossil CO_2 emissions are able to transition to permanent CO_2 abatement in a manner consistent with the necessary Union-wide emissions reductions trajectory needed prior to 2050.

3.7 Sectoral applications of CCUS and long-term business models

Achieving Permanent Carbon Dioxide Removals

There is a consensus that large-scale removal of CO_2 from the atmosphere will be required for **three main reasons:**

1. Further reducing net emissions in the near term;
2. Counterbalancing residual emissions to help reach net zero emissions in the midterm; and
3. Achieving and sustaining net-negative emissions post-2050 to address historic emissions and potential global temperature overshoot.

Collectively known as technology-based removals, the geological storage or mineralisation of atmospheric CO_2 obtained either through direct air capture or processing of biomass (provided it is climate-beneficial and not detrimental to the environment) are carbon removal solutions that offer measurable and permanent storage of CO_2 with extremely low risk of reversal. In particular, near-term opportunities for BECCS can be found in the pulp and paper, bioenergy and waste-to-energy sectors (See Appendix 1), which are associated with significant biogenic emissions (>100 Mt collectively).[59] Other options for potentially achieving large-scale carbon removals from biomass without CO_2 capture include biochar, and are sometimes collectively known as biomass with carbon removal and storage (BiCRS) or hybrid solutions.[60]

Currently there is little incentive to develop these technologies at the required scale in the EU, as value for removals is derived solely from voluntary markets with insufficient demand to support the cost of most early BECCS and (in particular) DACS plant. If EU and Member State targets for technological CDR are to be achieved, there is an urgent need to develop additional incentives, such as demonstration project funding followed by a move towards compliance markets for removals. For an initial deployment phase, dedicated business models can operate in parallel with voluntary markets, covering

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[58] Ramirez A R et al. (2020) *LCA4CCU Guidelines for life cycle assessment of carbon capture and utilisation*; Zakkour P and Cook G (2018) *Greenhouse gas emissions accounting for CO_2 capture and utilisation technologies*.

[59] Reinvent (2018) *Climate innovations in the paper industry*; Rosa L et al. (2021) *Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe.*

[60] ETC (2022) *Mind the gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*.

the funding gap between first-mover costs and existing revenues. Sweden has proposed a system providing 15-year contracts to BECCS plants, aiming to deliver 2 Mt/year of removals by 2030,[61] while a 'contract for difference'-based approach is under consideration in the UK to help meet a target of 5 Mt/year by 2030.[62] In the longer term, the value of technological CDR could be linked to a new market for removal certificates linked to sectoral, national, or regional targets, or potentially to the ETS; this should be addressed carefully and gradually to avoid compromising the prioritisation of emissions reductions.[63] In order to grow a market for permanent CDR with sufficient speed, various legal and regulatory measures should be considered at the EU and Member State levels, to ensure that legislation creates a business case for investment in permanent carbon dioxide removals. An example of a near-term policy to ensure this development would be the establishment of a dedicated funding stream for permanent CDR in the Innovation Fund.

As a fundamental prerequisite for these incentives and markets for CDR, there is a vital role for governments, including the EU and its Member States, to establish rigorous certification mechanisms that adequately value these higher-cost forms of real, measurable, permanent carbon removal. To help cultivate the required investment in technological CDR, the EU should:

- Set scientifically informed targets for carbon removals and establish a separate pillar for permanent removals alongside the ETS, ESR, and LULUCF.
- Identify the quantities of technological CDR that will be required at net zero based on residual emissions on a sectoral and national level.
- Develop a portfolio of removal options for Europe, emphasising that carbon removal must be real, permanent, measurable and additional to emission reductions.
- Ensure the forthcoming EU certification mechanism for carbon removal is based on full life-cycle analyses, ensures additionality and minimises uncertainties around monitoring, reporting, verification, permanence and leakage.
- Establish targeted funding mechanisms to support the early development and demonstration of real, measurable, permanent carbon removals.
- Develop a compliance market framework for hard-to-abate sectors to purchase removal 'credits' and a clear timeline for its adoption.
- Establish a strategy on whether fossil emissions and land-based emissions can be interchangeably balanced by geological and nature-based storage or separated.
- Set biomass standards to encourage the use of waste feedstocks and prevent new land clearing.

Furthermore, the importance of establishing a European network to transport and permanently store CO_2 will be an important enabler for the development of carbon removals in the future. In particular, there is potential for infrastructural synergies between capture of CO_2 via direct air capture, availability of clean energy and appropriate conditions for geological storage of CO_2.

CCUS for Industrial Processes

The EU's manufacturing industries are a key component of the wider economy, providing the critical materials – such as cement, steel, chemicals, plastics, alumnium and others – that will remain essential to our way of life for decades to come. As the EU transitions to a carbon neutral future, there will be new and growing demands on many of these materials, for applications such as wind turbines, photovoltaics, high-voltage transmission lines, electrified transport, and energy efficient buildings. However, these industries are also highly energy and emissions intensive, accounting for up to a quarter of total EU emissions (including energy-related emissions).[14] While many processes may be decarbonised via electrification, achieving net zero will mean also tackling 'hard-to-abate' emissions such as the process emissions from cement, lime, and chemicals, and emissions from remaining use of fossil fuels (or biomass) for driving high-temperature processes (**Figure 9**). The EU is in a position to lead the world in demonstrating that truly net zero-carbon industries are achievable, while ensuring that the thousands of direct and indirect jobs associated with these industries remain within the EU. CCUS is expected to play a critical role in fully decarbonising heavy industries and is currently the lowest cost or the only option for several sectors (**Figure 10**). As other countries, including the US, Canada, and the UK, accelerate the development of CCUS for low-carbon industry

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[61] Swedish Energy Agency (2022) *State aid for BECCS*.

[62] BEIS (2022) *Business models for engineered greenhouse gas removals*.

[63] ICAP (2021) *Emissions trading systems and net zero: trading removals*.

Figure 9: A Review of Projected CCUS Deployment in Key Industrial Sectors in 2030 and 2050 as a Percentage of Current Sectoral Emissions (Based on Various Literature Sources)[64]

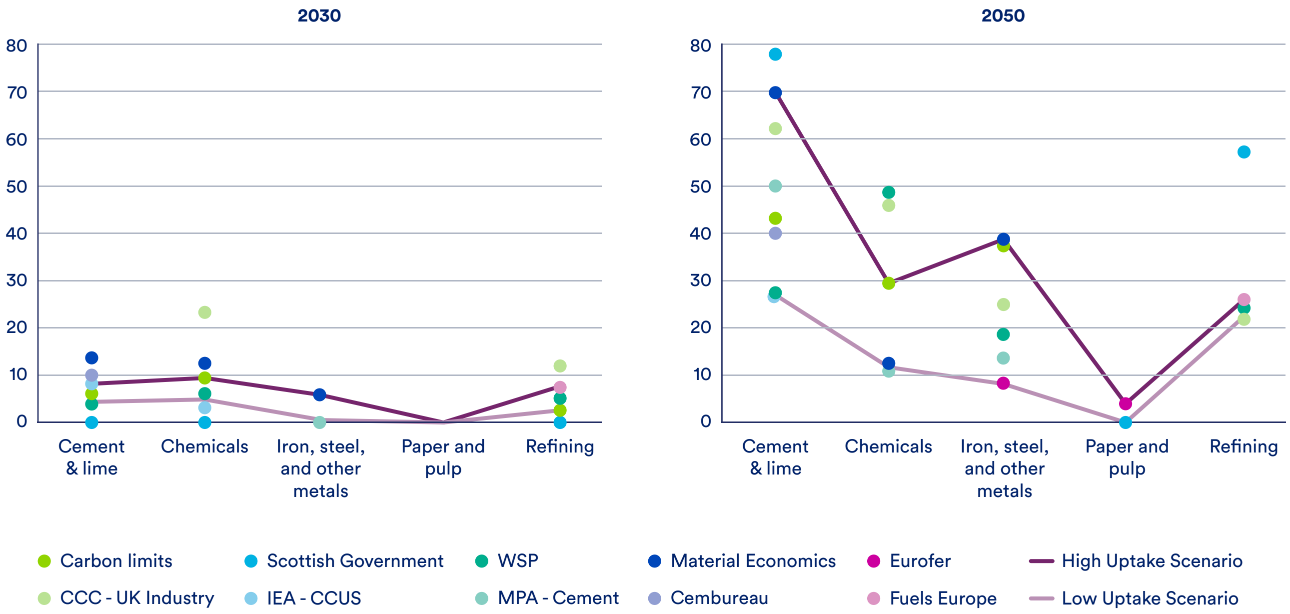
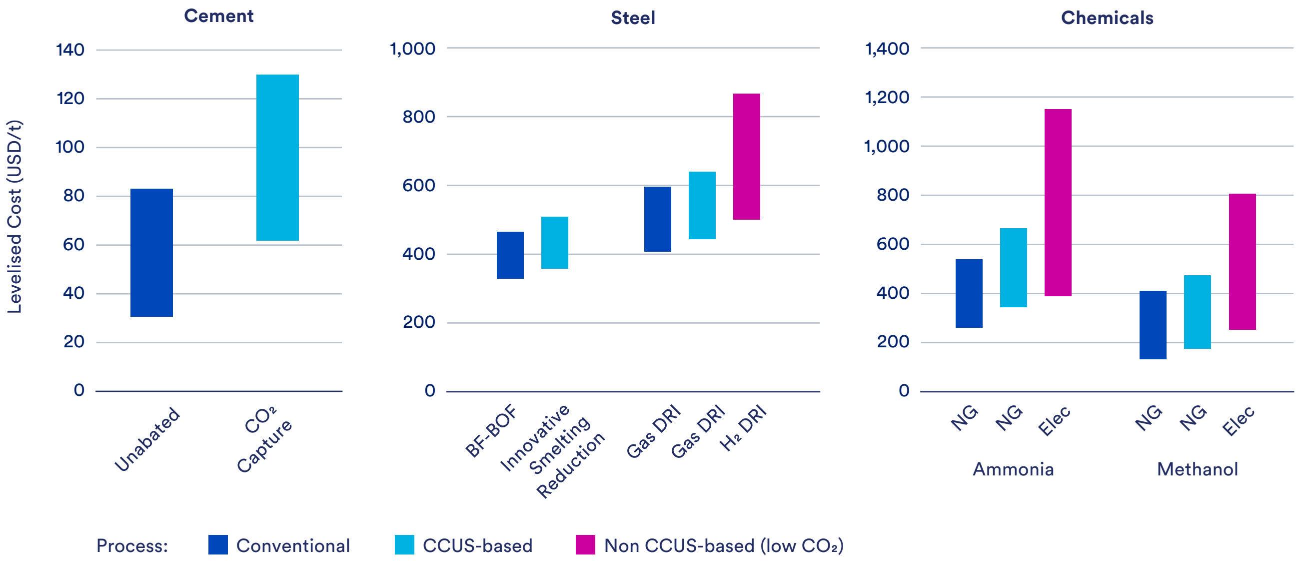


Figure 10: Estimates of Levelized Cost of Producing Low-Carbon Cement, Iron and Steel, and Chemicals Via Different Production Routes[65]



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[64] Element Energy (2022) *European CCS potential and economic impacts*. Note: Paper and pulp emissions are primarily biogenic and over 90 $MtCO_2$/year, so present an opportunity for BECCS (Capturemap.com, Endrava, 2022).

[65] Page 174 of IEA (2020) *Special report on carbon capture utilisation and storage. CCUS in clean energy transitions*. Note: recent gas price increases will affect the near-term cost of nearly all decarbonisation solutions relative to this study.

(*See Box 2 for US initiatives*), there is growing urgency for the EU to ensure its industries can also remain competitive and viable in a low-carbon future.

Many of these sectors are yet to see the adoption of CCUS for a full-scale plant anywhere in the world. However, supported by initiatives such as the Innovation Fund, several processes may be first pioneered in the EU. As for most applications of CCUS, it will be necessary to create a policy-backed commercial case for early projects – beyond a first-of-a-kind plant in each sector – during a transition period towards full exposure of industry to the carbon price. This will ensure that the technologies and infrastructure required for widespread commercial deployment are available and cost-optimised in time. From 2030, decarbonised industry should also begin to move from a reliance on government support towards decarbonisation driven by market demand and standards for low-carbon products and services. The relative cost increase in the production of low-carbon raw materials such as steel and cement is much less significant, and therefore easier for consumers to absorb, when applied to end-use products such as cars or buildings.[66] EU policy can help accelerate this transition by developing low-carbon product certification, setting regulatory standards for end-user products, and seeding initial demand through public procurement initiatives. Many of these measures can build on existing or forthcoming legislative packages such as the Proposal for Ecodesign for Sustainable Products Regulation and the Construction Products Regulation.

The industrial decarbonisation challenge continues to evolve, as processes change and new low-carbon technologies become available or reduce in cost, and the term ‘hard to abate’ can be broad and poorly defined. For some industries, such as cement, lime, and the production of certain petrochemicals, there are currently no viable alternatives to CCUS for decarbonisation. Other industries, including steel, may have alternative routes available, often based on low-carbon fuels or feedstocks such as hydrogen or biomass (**Figure 9**); however, there is often no ‘one size fits all’ solution or one technology that can decarbonise an entire facility, particularly where access to low-carbon electricity or hydrogen is constrained or slow to develop. Europe’s heavy industry plants will continue to assess and identify their optimum techno-economic pathways for decarbonisation, and policymakers may determine that subsidies for technologies such as CCUS are conditioned on a thorough demonstration that alternative solutions are not viable or not yet available (such a requirement is a feature of the Netherlands’ SDE++ support scheme; *see Appendix 2*). The most effective means of achieving rapid, market-driven decarbonisation of this sector – thereby minimising cumulative emissions – will be to ensure maximum access to enabling infrastructure of all kinds, be that CO_2, hydrogen, or low-carbon electricity. CO_2 capture is also an energy intensive process and, while many emitters can make use of available waste heat, there will be an important dependence on access to low-carbon energy for some industries – particularly cement and lime plants.

In addition to the broad financial and infrastructure support measures listed above, steps to maximise the decarbonising potential of CCUS in industry could include:

- Creation of an Important Project of Common European Interest (IPCEI) for CCUS and an industrial partnership on the model of the Hydrogen Alliance, as well as appropriate recognition of CCUS in other relevant IPCEI
- Technology-neutral funding for industrial decarbonisation through mechanisms such as carbon contracts for difference, accessible beyond the first-of-a-kind plant phase.
- ‘Best available technology’ standards and performance-linked incentives and regulations to ensure high capture rates are maintained by CCUS facilities, and alternative technologies assessed where available.
- Encouraging Member States and industrial stakeholders to identify and rank hard-to-abate emissions, develop decarbonisation roadmaps for key industrial sectors that are viable and mutually achievable (i.e., not dependent on the same resources), and adequately address industrial decarbonisation in NECPs.
- Rigorous product certification to underpin demand for low-carbon products.
- Implementing public procurement of low-carbon products, such as concrete and steel.
- Introducing carbon intensity limits or sectoral targets for low-carbon products in end-use sectors such as construction and vehicles.

See the Appendices for short case studies of the issues concerning CCUS deployment in key industrial sectors.

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[66] Rootzen J, Johnsson F (2016) *Paying the full price of steel – perspectives on the cost of reducing carbon dioxide emissions from the steel industry.*; Rootzen J and Johnsson F (2016) *Managing the costs of CO_2 abatement in the cement industry*.

CCUS in the Power Sector

As wind and solar power have achieved dramatic cost reductions over the past decade, the EU's early political focus on CCS as a decarbonising technology for fossil-fired power plants has greatly diminished. However, fossil fuels still provide around a third of the region's power and account for around 25% of its CO_2 emissions. Large coal power plants have been commissioned as recently as 2020 (over 4.4 GW) and significant new gas power capacity is under construction or planned in many countries (estimated at nearly 30 GW).[67] Efficient gas-fired power plants in particular are expected to remain an integral part of the energy mix in several member states as renewable capacity is expanded and coal power phased out. These plants are able to provide flexible back-up to intermittent generation and could act as a rapidly deployable complement to large-scale, long-duration forms of energy storage, such as power to hydrogen. Given the scale of the challenge in achieving rapid grid decarbonisation and the number of existing and planned fossil-based assets, CCUS-equipped power plants can play a role in accelerating this transition and reducing the currently significant 'locked in' emissions that will be accrued to 2050.

As utility power plants generally constitute relatively large CO_2 point sources compared with most industrial emitters, they can offer large-scale abatement opportunities, and their potential captured emissions must be carefully considered in CO_2 infrastructure planning. In this regard, in some localities CCUS-equipped power plants may act as CO_2 infrastructure hubs by enabling economies of scale.

The addition of CCUS to biomass-fired power plants, such as existing coal or gas plants converted to operate on sustainably sourced solid biomass or biogas, can enable these facilities to also provide permanent CDR through BECCS. Furthermore, biomass-fired combined heat and power (CHP) plants offer a promising opportunity for integration with CO_2 capture, as much of the energy penalty for capture can be reclaimed as useful heat.[68] Recommendations for potential adoption of CCUS in the power sector include:

- Consider a regulatory requirement for CCUS (with high capture rates as 'BAT' standard) as an obligation for all new fossil capacity.
- Consider additional electricity market mechanisms to support the viability of low-carbon, dispatchable power generation and ensure priority dispatch over higher carbon intensity sources (an example is the Dispatchable Power Agreement proposed in the UK).[69]
- Identify fossil-fired assets which can be usefully repurposed for delivering BECCS.

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[67] S&P Global Platts (2022) *World Electric Power Plant database*.

[68] Gustafsson K et al. (2021) *BECCS with combined heat and power: assessing the energy penalty*.

[69] BEIS (2021) *Dispatchable power agreement: business model summary and consultation.*

SECTION 4

Conclusions

There is growing scientific and political consensus that the widespread deployment of CCUS (on the order of 100s of Mt/year) will be required if the EU is to achieve its climate goals. As this need becomes apparent through long-term analysis of viable decarbonisation pathways on a national level, several Member States – particularly in the North Sea region – have begun to actively support and deploy the technology. Now, there is an important role for the Commission to play in coordinating, optimising, and accelerating these developments – which will necessarily take place on a cross-border basis – while also ensuring that no Member State or region is left behind in their efforts to decarbonise using CCUS technologies. Without this leadership, it is difficult to see how CO_2 capture, transport, utilisation and storage will develop sufficiently quickly and at the required scale, and industries will not be able to deliver in accordance with the European Green Deal. To this end, this Vision document provides a first step and set of recommendations towards a comprehensive CCUS Strategy for the EU.

Appendix 1. Industry Case Studies

Cement and Lime

The cement and lime industry is one of the EU's most greenhouse gas-intensive industrial sectors, accounting for over 3% of the region's greenhouse gas emissions.[70] As around two thirds of the CO_2 released by cement and lime plants are associated with the calcination of calcium carbonate, these 'process emissions' are impossible to avoid through fuel switching or electrification and can only be addressed with CCUS. The cement industry therefore features heavily in current plans to deploy CCUS at scale in the region, with one project currently under construction at Brevik in Norway, and a further four projects selected under the first two calls of the Innovation Fund in France, Bulgaria, Germany, and Poland (in addition to a lime plant in France). Other strategies for cement and lime decarbonisation include improving process efficiencies (generally already maximised at EU sites), switching to low-carbon fuels or electricity for process heating, and in the case of cement, using clinker substitutes such as blast furnace slag. However, most industry projections foresee a role for CCUS in up to around half of the CO_2 abatement required to reach net zero. In the long-term, lower-carbon alternatives to cement – such as magnesium oxide-based materials – may become technically mature, but these are not anticipated to make a significant contribution within the timeframe of net zero by 2050.

There are several technical approaches being developed to capture CO_2 from cement and lime plants: First, post-combustion treatment of standard flue gases using CO_2 capture solvents – as employed at Brevik. Second, an oxyfuel process, as proposed under the K6 project in France and at Lägerdorf in Germany, in which combustion and calcination is carried out in a mixture of oxygen and CO_2, producing a relatively pure CO_2 stream. Third, the cement kiln can be indirectly heated, thereby separating CO_2-rich process emissions from combustion-related emissions, as currently trialled at the pilot scale under the 'LEILAC' project in Belgium (and its planned scale-up in Germany); this process could be most effectively combined with indirect heating through electrification or another low-carbon heat source. Each of these technologies merits further development, as the optimum solution for a given plant will depend on a number of site-specific factors, including availability of waste heat, low-carbon fuels or electricity, and oxygen (potentially as electrolyser by-product). Owing to the relatively low availability of waste heat within cement plants, the energy demand associated with all forms of CO_2 capture technology present a challenge for the sector, and potential requirements for expanded energy infrastructure (such as renewable power supply and delivery) should be considered.

As cement and lime plants are generally located close to quarries and local customers, rather than close to other industries in clusters, ready access to CO_2 transport infrastructure poses a challenge for many sites in the EU. The projects currently selected under the Innovation Fund have proposed the use of a range of transport options to link to storage sites, including rail, ship, and pipeline – sometimes in combination. In some cases, local CO_2 utilisation may prove to be a useful interim solution.

Once the capture technologies are fully commercialised and CO_2 infrastructure widely available, the production of low or zero-carbon cement may be most effectively incentivised through market demand in the buildings sector. This could begin with procurement of low-carbon cement for public projects, and extend to the private sector through regulatory measures such as the incorporation of carbon footprints in buildings standards.

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[70] SWD (2020) 176, *Impact assessment accompanying the document 'Stepping up Europe's 2030 climate ambition'*

Steel

The iron and steel sector is the largest source of industrial emissions in the EU, accounting for over 5% of total greenhouse gas emissions.[71] Steel is an iron alloy that can be made through two main routes: 'primary steel' from the processing of iron ore, and 'secondary steel' from the recycling of scrap steel in an electric arc furnace (EAF). Secondary steel is much less carbon-intensive than primary steel, and currently represents around 40% of European production, but there are limits to how much steel can be recycled, based both on suitable scrap availability and quality requirements of the end product. A significant proportion of primary steel production will therefore continue to be required in future.

Nearly all the EU's primary steel is produced via the highly carbon-intensive blast furnace route, in which iron ore is chemically reduced with coking coal at high temperatures, before further processing to steel in a basic oxygen furnace. Many of the region's steel producers are now pursuing a shift towards the alternative direct reduced iron (DRI) process, which can be fuelled by natural gas (roughly half as carbon intensive as the blast furnace route) or even entirely on low-carbon or renewable hydrogen – potentially cutting CO_2 emissions to much lower levels. Currently, the DRI process (mostly using natural gas) represents only around 5% of global steel production, and only one plant is operating in the EU. The principal challenge in transitioning all blast furnace sites to a low-carbon form of DRI is in sourcing sufficient volumes of hydrogen; studies indicate that over 60 billion m^3 (5.4 Mt) of hydrogen would be needed to match the 92 Mt of EU steel production in 2018. If derived entirely from renewable-powered electrolysis, this would require nearly 350 TWh of renewable generation, or more than double total solar power output in the EU today.[72]

While switching blast furnace-based sites to DRI will be an important pathway for primary steel decarbonisation in the EU, some industry actors also anticipate a complementary role for CCUS. Potential applications include:

- Production of low-carbon hydrogen from methane for hydrogen-DRI.
- Capture of CO_2 from DRI units operating on natural gas – potentially during a transition to 100% hydrogen conversion, or long-term if hydrogen supplies are inadequate.
- Capture of CO_2 from remaining blast furnaces – potentially alongside a new DRI unit at the same site.
- Capture of CO and CO_2 from blast furnaces for CCU applications.
- Capture of CO_2 from electric arc furnaces (particularly if alloying carbon is added at this stage).
- Capture of CO_2 from auxiliary processes and downstream processing that are difficult to electrify

One of the challenges of deep decarbonisation via the hydrogen-DRI route is the need to introduce alloying carbon to the iron at some point in the process; in conventional steel making, this carbon would come from the coking coal or natural gas fuel. In a hydrogen-based DRI process, biogenic carbon could potentially be used by introducing a small proportion of biogas to the DRI reactor or introducing biochar to the EAF. Alternatively, a source of higher-carbon iron can be added to the EAF, potentially making it useful to retain a CCUS-equipped blast furnace on site.

The capture of CO_2 from blast furnace gas has only been trialled at pilot scale worldwide, for instance, under the EU-funded STEPWISE project. CCS at a full-scale DRI unit in Abu Dhabi has been operated since 2017, using a commercial process that inherently captures a portion (~40-50%) of the CO_2 produced. Given the vast scale of steel emissions in the EU and globally, encouraging further development of CCUS in this sector would be a prudent strategy for ensuring deep decarbonisation and resilience to future hydrogen or renewable energy scarcity. With 330,000 jobs and 2.6 million indirect jobs linked to the sector, it is imperative that a low-carbon steel industry can be retained in the EU.

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[71] Ibid.

[72] Sasiain Conde A et al. (2021) *Decarbonization of the steel industry. A techno-economic analysis.*

Waste-to-energy

Waste-to-energy (WtE) plants use heat derived from the combustion of waste streams to generate power or directly supply heat for applications such as district heating. They play a double role in today's society. First and foremost, WtE serves a hygienic function by treating household and industrial residual waste that cannot or should not be recycled. Furthermore, by treating the residues created from sorting and recycling activities, WtE plants also acts as a reliable sink for pollutants. Secondly, WtE facilities make use of the embedded energy in the residual waste for the production of electricity, heating, and cooling. In 2021, the amount of primary energy generated by WtE in Europe was equivalent to 13.8 billion m^3 of natural gas. This corresponds approximately to 9 % of the natural gas imports to the EU from Russia (155 billion m^3) that year.[73]

Apart from the CO_2 emission savings that can be achieved by substituting fossil fuels with WtE, WtE further contributes to reducing greenhouse gas emissions by facilitating landfill diversion, meaning that waste is redirected from landfills to treatment routes higher in the waste hierarchy. Decomposing waste in landfills generates methane – a greenhouse gas that is 28 times more potent than CO_2 on a 100-year perspective and 86 times more on a 20-year perspective.[74] In addition, further CO_2-eq savings can be achieved in WtE plants through the recovery of valuable raw materials, such as ferrous and non-ferrous metals retrieved from the incinerator bottom ash (IBA) after the incineration process.

Despite this important climate benefit, there are still emissions from WtE plants that need to be tackled. Household waste alone accounts for 3% of EU greenhouse gas emissions (and 5% globally).[75] There are almost 500 WtE plants operating across the EU, and in many cities these are among the largest emission point sources. Many plants have already made plans to install CO_2 capture, often driven by ambitious municipal decarbonisation targets and the fact that no alternative decarbonisation options are available. Waste recycling rates have steadily improved in the EU, but a proportion of non-recyclable waste is expected to remain in the foreseeable future. According to the IPCC, the integration of WtE and CCS could enable waste to be a net zero or even net negative emissions energy source. For example, in Europe only, the integration of CCS with WtE facilities has the potential to capture about 60 to 70 million tons of carbon dioxide annually.

The CO_2 generated by WtE must be differentiated into two categories according to its origin:

- Fossil CO_2 from the combustion of fossil-based waste, such as residual plastics.
- Biogenic CO_2 from the biogenic fraction of different waste streams, such as residual paper and cardboard, wood, leather, food, and green residues that are contaminated and thus non-recyclable.

Given that around 50-85% of the incinerated waste streams are of biogenic origin, corresponding to a biogenic share of 40-60% of the emitted CO_2, there is also a large potential role for WtE plants in providing CO_2 removal through BECCS (as acknowledged by Vice-President Timmermans). According to ETH Zurich, the current WtE plants in Europe could remove 35 Mt of CO_2 from the atmosphere yearly if they were equipped with CCS.[76] This without demanding any further land-use, which could present a limitation on BECCS plants using conventional biomass sources.

ARC's Amager Bakke WtE plant in Copenhagen has trialled a CO_2 capture technology and has proposed a full-scale system that would be an anchor project withing the planned 'C4' cluster – a collection of public utilities in the municipality exploring shared CO_2 infrastructure. A commercial CO_2 capture system is also operational at AVR's plant in Duiven, Netherlands, where 60 kt/year of CO_2 is supplied to local greenhouses. Among the EU's immediate neighbours, WtE plants comprise nearly 40% of applications to the UK CCUS funding process, while in Norway, Hafslund Oslo Celsio has begun construction of the world's first full-scale capture facility with permanent geological storage of 400 000 kt/year in the North Sea, having received funding from the Norwegian Longship project, the municipality, and other investors.

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[73] CEWEP (2022) *Waste to Energy climate roadmap*.

[74] Wang et al. (2020) *An assessment of the dynamic global warming impact associated with long-term emissions from landfills.*

[75] Gautam M and Agrawal M (2020) *Greenhouse gas emissions from municipal solid waste management: A review of global scenario.*

[76] Rosa L et al. (2021) *Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe.*

Aside from local decarbonisation targets, there is currently little incentive to capture CO_2 from WtE plants, which remain outside of the ETS except for in Denmark and Sweden. However, the current revision of the ETS Directive may see WtE emissions subject to the carbon price. In addition, several countries have national incineration taxes for the fossil CO_2 emissions. While this can help drive decarbonisation of the sector, policy should be carefully designed to avoid diverting waste to landfill or export from the EU and, above all, ensure that recycling rates continue to be maximised. As for other industries, providers of low, zero- or carbon negative waste treatment services will require new incentives to cover the cost gap with conventional disposal and ensure they remain competitive. This could potentially be through a contract for difference model, direct gate fee support, or project grants until there is sufficient market demand for CO_2-neutral waste handling services. The sale of carbon removal certificates may also play a key role in financing future WtE CCS plants.

EU policy under the Waste Directive currently aims to significantly reduce mixed bio-waste streams through separate collection, composting and anaerobic digestion. However, with increased source separation of plastics and the increase of bio-based products in the market, the amount of biogenic content in residual waste could potentially increase.
Going forward, the EU and national governments should strive to equip existing plants with CCUS technology, and all new waste-to-energy plants should be built with CCUS. The future role of CCUS in the waste sector should be properly integrated into the EU's overarching strategies for the circular economy, sector integration, climate finance and the carbon removals certification scheme.

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[76] Rosa L et al. (2021) *Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe.*

Appendix 2. Country Case Studies

Denmark

Political framework

In the last few decades, Danish energy sources have gradually transitioned from fossil fuels to renewables, and by 2019 Denmark reduced its overall emissions of greenhouse gasses by 39.6% from 1990 levels.[77] This was primarily the result of smart and cautious planning and the right investment choices. During the last couple of years, Denmark has built upon this legacy, setting some of the world's most ambitious climate goals and emissions reduction targets.

On the 6th of December 2019, 8 out of the 10 parties in the Danish Parliament agreed on a legally binding national Climate Act.[78] This included a legally binding target to reduce greenhouse gas emissions by 70% by 2030 (compared to 1990 levels). Since the agreement on the Climate Act, Denmark has worked towards broad political agreements on emissions reductions, concluding a Climate Agreement for Energy and Industry[79] in June 2020, in which a broad majority of parties in the Danish Parliament agreed that going forward, it must be possible to capture, transport, utilise and store CO_2 in Denmark, as well as to transport captured CO_2 across national borders, provided it takes place under sound safety and environmental conditions. The agreement allocates a total of approximately DKK 16.6 billion (around €2.2 billion) in 2023 prices to the development and implementation of these technologies.

Additionally, a Roadmap for the Capture, Transportation and Storage of CO_2 has been agreed upon through the political agreements from the 30th of June 2021 and the 14th of December 2021.[80] The agreements present an overall strategy for carbon capture, and storage (CCS) in Denmark and express the ambition to roll out CCS on market terms in the long-run, allocating funds to the Geological Survey of Denmark and Greenland (GEUS) to investigate potential storage sites with the aim of making Denmark a European CO_2-storage hub and establishing six regional clusters, as well as ensuring the right legislation and infrastructure is in place.

Supplementing the above, the annual Budget Agreement (Green Chapter) 2022 from the 4th of December 2022 allocates approximately DKK 2.6 billion (€350 million) in 2023 prices to the capture of CO_2 and the achievement of negative emissions (**Table 2**). Moreover, a broad political agreement on a carbon tax was reached on the 24th of June 2022 which allocated a further DKK 19.5 billion (€2.6 billion) to CCS, making the combined available funding for CCUS approximately DKK 38.2 billion (approximately €5.2 billion), which is projected to result in the storage of 3.2 Mt CO_2 in 2030.

Implementation

The combination of the above-mentioned policies sets the policy framework which guides Danish CCS efforts, concentrating on making storage sites available, enabling cross border transportation of CO_2, as well as establishing mechanisms to encourage emitters to capture their CO_2.

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[77] Danish Energy Agency (2021) *Denmark's Climate Status and Outlook 2021.*

[78] Denmark (2020) *Climate Act.*

[79] Danish Parliament (2020) *Climate Agreement for Energy and Industry.*

[80] Danish Parliament (2021) *A roadmap for the capture, transport and storage of CO_2.*

Table 2: Denmark's Subsidy Schemes for CCS

	CCUS	NECCS	GSR
Eligible for funding	Negative emissions and reductions from technological flue gas processes	Negative emissions from technological processes	Negative emissions and reductions from technological processes, agricultural sector excluded
Eligible sources of CO_2	Fossil and biogenic	Biogenic (including DACCS)	Fossil and biogenic (including DACCS)
Contract period	Up to 20 years per contract w/ opt-out option w/ retention penalty	Up to 8 years per contract w/ opt-out option (limited retention penalty)	Up to 15 years per contract w/ opt-out option (limited retention penalty)
Pre-financing	No	Yes	No
First reduction year	2025/26	2024/25	2026/27
Support period	2024-2049	2023-2032	2026-2043
Budget (2023-prices)	16,6 mia. kr.	2,6 mia. kr.	19,5 mia. kr.

In this respect, Denmark has accepted the 2009 amendment to Article 6 of the London Protocol and informed the Secretary-General of the International Maritime Organization (IMO) of its intentions to make use of the provisional application of the 2009 amendment to Article 6 of the London Protocol according to resolution LP.5 (14). Both notifications were deposited with the IMO secretariat on the 27th of January 2022. Moreover, on the 26th of September 2022, Denmark signed the world's first bilateral arrangement with Belgium on the transportation of CO_2 with the purpose of permanent geological storage.[81]

Denmark's first tender for CO_2 storage permits opened for permit applications on the 15th of August 2022 until the 1st of October 2022 for exploration and storage of CO_2 in a delimited area in the Danish part of the North Sea. To enable new storage sites, GEUS is tasked with identifying potential storage sites in Denmark from 2022-2024. Potential storage sites can be located either offshore, near-shore or onshore. Since establishing storage sites is considered a lengthy process and factors such as local support are important for onshore development, it is necessary to engage with the relevant regions, municipalities and citizens from an early stage. Eight new potential storage sites have already been identified, and GEUS has conducted seismic data gathering in Stenlille and Havnsø, with plans to do the same in Gassum, Thorning, Rødby and Jammerbugt (**Figure 11**). Simultaneously, the Danish Energy Agency is conducting an Environmental Impact Assessment of the structures. The ambition is to enable these areas for a public tendering license round in 2024.

In some cases, potential storage sites will be located close to Danish emitters, but there will also be a need for the transportation of CO_2 to storage sites. The Danish Energy Agency has identified six clusters in Denmark with considerable emissions (**Figure 12**). These are located around the cities of Copenhagen, Odense, Fredericia, Esbjerg, Aarhus and Aalborg. The relevant stakeholders in these clusters are tasked with presenting their recommendations on possible transport infrastructure and ownership models as well as considering synergies with each other and the transportation of CO_2 from other countries to ensure consistency. The final recommendations will be delivered on the 2nd of January 2023.

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[81] MoU (2022) between the Minister for Environment of the Flemish Region and The Federal Minister for the North Sea of Belgium and The Minister for Climate, Energy and Utilities of Denmark on Cross Border Transportation of CO_2 With the Purpose of Permanent Storage.

Figure 11: The Distribution of Denmark's Potential CO_2 Storage Resources, Showing the Eight Identified Storage Sites and Principal Point-Source Emitters

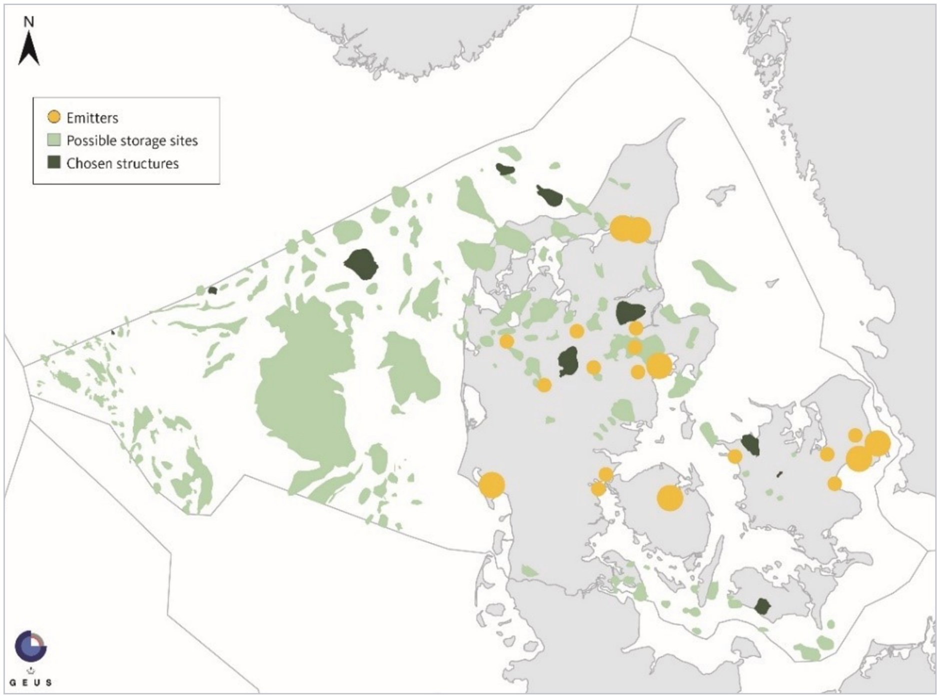
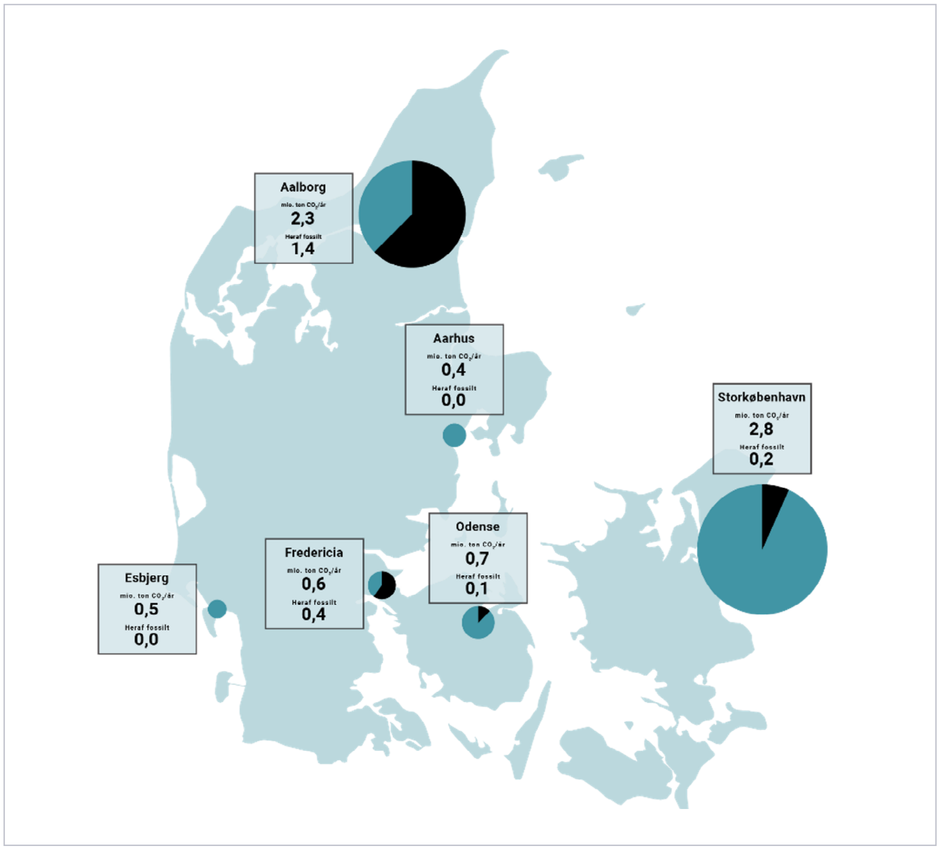


Figure 12: The Six Emissions-Intensive Clusters Identified by the Danish Energy Agency

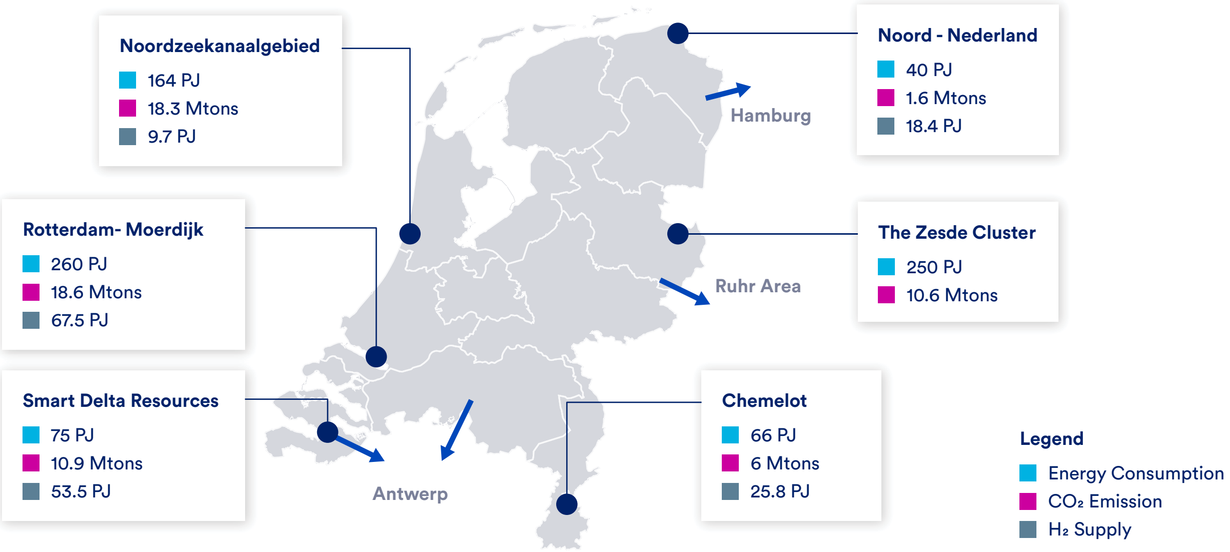


The Netherlands

A combination of factors has contributed to the Netherlands status as an early-mover for CCUS deployment in the EU, including significant regional concentrations of industrial emissions (clusters), promising geological storage resources, and strong climate ambitions. However, strong local opposition led to the 2010 cancellation of a CCS project associated with Shell's Pernis refinery, with the result that onshore storage in the country was banned under the national implementation of the CO_2 Storage Directive. The ROAD project aiming to capture CO_2 from a coal plant in Rotterdam was also cancelled, owing partly to implementation of a coal phase out policy. Despite these false starts, CCUS returned to the climate agenda as part of the 2019 Climate Agreement, which identified a key role for the technology in decarbonising industry to achieve the targeted 49% emissions reduction by 2030.[82] Through extensive dialogue with stakeholders from across industry, academia, and civil society, restrictions on the planned CCUS deployment were introduced, including a 10.2-Mt cap on the total CO_2 capture to be subsidised,[83] a requirement for industry to demonstrate that no other cost-effective alternatives for decarbonisation are available (the 'sieve'), and a commitment to end subsidies to CCUS by 2035. Five key industrial clusters were identified in the Agreement, with a sixth (the Zesde cluster) sometimes considered in later analysis (**Figure 13**).[76]

In order to fund the deployment of CCUS in industry, the Netherlands' Sustainable Energy Transition scheme (Stimulering Duurzame Energietransitie, or SDE) for supporting renewable deployment was expanded in 2020 to include carbon capture, utilisation and storage and other decarbonisation technologies. Under this expanded 'SDE++' scheme, projects compete for funding on the basis of the cost of carbon abated; this takes place over four separate phases with increasing maximum subsidy, going up to 300 €/t CO_2 in the final phase.[42] Successful projects are then able to receive a subsidy amounting to the difference between their actual operating cost and the market value of the product generated, calculated on an average annual basis for a 12 or 15-year contract period.

Figure 13: The Six Major Industrial Clusters in the Netherland[84]



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[82] Government of the Netherlands (2019) *The Climate Agreement.*

[83] This cap comprises 7.2 Mt for industry and 3 Mt for power (aimed at power plants associated with Tata Steel's IJmuiden plant). In 2021, the cap for industry was raised to 9.7 Mt.

[84] DNV (2022) *Industrial decarbonization utilizing CCS and hydrogen in the Netherlands*.

Of €4.76 billion awarded in the 2020 round of the SDE++, bids for funding CO_2 capture and storage from four emitters in the Port of Rotterdam were successful in securing guaranteed funding of up to €2.1 billion. The 2.5 Mt/year of CO_2 captured by these combined emitters will make use of a CO_2 pipeline and near-shore storage site service known as the Porthos project. Porthos will use a storage site partly developed under the ROAD project, whose capacity is limited to the four contracted plants, while the onshore pipeline will be sized to accommodate an additional 7.5 Mt/year. Carbon capture projects also represented the majority of applicants to the 2021 round of the SDE++ scheme, with eleven applicants and an average carbon avoidance cost of only 75 €/t.[85] However, these projects were unable to proceed as they could not demonstrate the feasibility of access to storage within the required time period of five years. SDE++ funding also extends to CCU projects, including the use of CO_2 in greenhouses for agriculture, where CO_2 abatement is primarily through the avoided use of gas-fired heaters. The Twence WtE plant is currently installing 100 kt/year capture for this purpose. The total annual budget earmarked for the SDE++ scheme varies; it was €5 billion in 2020, but the government has allocated €13 billion to the scheme for the 2022 round. In the 2022 round, CCS projects represented the largest share of bidders, with a total request of €7.1 billion (mostly resubmissions from the 2021 round).

Some other carbon capture clusters, utilisation and storage projects have been proposed in the Netherlands. Among these, under the name of Carbon Collect Delta, emitters in the North Sea Port – a cross-border port region shared with Belgium – are collaborating with the aim of capturing and storing up to 6.5 Mt/year by 2030. In September 2021, TotalEnergies, Shell, EBN, and Gasunie formed a partnership to develop depleted offshore gas fields to the north-west of the Netherlands, known as the Aramis projects.[86] This site would be fed by a pipeline from Rotterdam with a maximum capacity of 22 Mt/year, although the project will initially aim to process 5 Mt CO_2 per year. In 2022, Neptune Energy announced the development of the L10 gas field for CO_2 storage, also with the ambition to store 4-5 Mt/year.[87] If these new storage sites develop on schedule, the next round of the SDE++ will be able to accept bids from CO_2 capture and storage projects.

Croatia

Nearly 40% of Croatia's emissions are concentrated in energy and industrial production processes.[88] Much of these emissions occur in the power sector, the production and refining of hydrocarbons, as well as cement and fertiliser production.[89]

Until now, the Croatian Government has not made carbon capture and storage a high political priority. For example, the country's National Energy and Climate Plan for the period 2021-2030 only references carbon capture and storage when outlining that coal and natural gas power plants "will not be technologically advanced except in the context of the development of carbon capturing and storage, CCS". However, carbon capture and storage is considered as potentially important in the long term. The Low Carbon Strategy (NN 63/21) envisages the application of CCU and CCS technology in gas-fired power plants and in the cement industry after 2040 as part of the Accelerated Energy Transition (NU2) scenario.

However, there is some commercial interest in carbon capture and storage in Croatia. Croatia has included investments into two specific projects as part of its Recovery and Resilience plan.[90] The first investment is a €12.7 million grant for a pilot project by Petrokemija Kutina, an ammonia and fertiliser production facility in Kutina, Croatia, which would capture CO_2 and transport it by the existing gas pipeline (which needs to be repurposed and renovated) to depleted oil and gas fields in Ivanić Grad, Croatia. The project aims to capture 190,000 tons of CO_2 per year, leading to a total of 5 Mt of CO_2 to be stored over the lifetime of the project. The second investment is a €33.2 million grant for a CCS installation to be included as part of an ethanol refinery project in Sisak, Croatia. The project aims to capture 55,000 tons of CO_2 per year, which will be transported to depleted gas fields approximately 40 kilometres away from the site.

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[85] Energeia (2021) *SDE++ ruimschoots overvraagd, vooral door CCS-projecten*.

[86] Gasunie (2021) *TotalEnergies, Shell Netherlands, EBN and Gasunie form partnership to develop an offshore CCS-project*.

[87] Neptune Energy (2022) *L10 carbon capture and storage*.

[88] European Parliament (2021) Briefing: *Climate action in Croatia*.

[89] Ibid.

[90] Republic of Croatia Ministry of Justice and Public Administration (2021) *Recovery and Resilience Plan*.

Poland

Responsible for 10.5% of the EU's total greenhouse gas emissions, Poland is among the largest emitting Member States.[91] As approximately 68% of Poland's emissions come from the energy and industrial sectors, there is considerable opportunity for carbon capture and storage to achieve significant reductions of Poland's CO_2 emissions.

However, on a strategic level, Poland lacks a comprehensive approach towards carbon capture and storage development. The country's National Energy and Climate Plan for the period 2021-2030 merely references carbon capture and storage in passing,[92] while Energy Policy of Poland until 2040 declares that CCS technologies will be researched and implemented, but provides no in-depth strategy describing how carbon capture and storage will be developed in Poland and includes no specific targets or and timeline.[93] In addition, substantial regulatory restrictions are imposed in Poland's transposition of the CCS Directive, which includes a minimum capacity threshold for CCS installations, excludes the deployment of pilot projects and prohibits onshore CO_2 storage.[94]

However, there are several planned carbon capture and storage projects in Poland, such as at a combined heat and power (CHP) station in Przemyśl[95] and the Poland-EU CCS Interconnector – an open access multi-modal liquid CO_2 import-export terminal in Port of Gdansk. The project was included in the fifth list of energy Projects of Common Interest (PCIs) and is aiming to begin operation from July 2026, potentially transporting 2.7 million tonnes of CO_2 per year between 2025-2030 and reaching 8.7 million tonnes of CO_2 from 2030 to 2035.

Two large-scale carbon capture and storage projects have also been funded in part by the EU, both of which have cement applications. The Górażdże cement plant owned by Heidelberg Materials, will pilot an innovative post-combustion enzyme-based carbon capture technology within the €18 million ACCSESS project co-funded by the EU Horizon 2020 programme. The project coordinated by Sintef Energi (Norwegian research institute) will explore aspects of transporting CO_2 from sites in mainland Europe to the Northern Lights storage facility in Norway, including all regulatory aspects of cross-border CO_2 transport. The project will run for 48 months, from May 2021 to April 2025.

In addition, the GO4ECOPLANET project, run by Lafarge Cement S.A. aims to create an end-to-end CCS chain starting from CO_2 capture and liquefaction at the Kujawy cement plant, transporting liquid CO_2 by train to the Gdansk terminal and then shipping the CO_2 to offshore storage sites. The project has been selected in the second call for large-scale projects by the EU's Innovation Fund. Both of these projects, the first of their kind in Eastern Europe, will be among the first movers for large-scale decarbonisation in the region, as well as in the cement industry.

While bringing these projects into operation will be important to showcase the feasibility of carbon capture and storage as a critical climate solution for Poland, developing critical CO_2 transport and storage infrastructure remains a significant priority for full-scale deployment to be achieved in the country.

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[91] European Parliament (2021) *Briefing: Climate action in Poland*.

[92] Polish Ministry of Climate and Environment (2019) National Energy and Climate (ENCP) Plan for 2021-2030.

[93] Polish Ministry of Climate and Environment (2021) Energy Policy of Poland until 2040 (EPP2040).

[94] Domagoj Vulin et al. (2021) Assessment of current state, past experiences and potential for CCS deployment in the CEE region Croatia.

[95] Promoted by PGNiG.

Appendix 3: Working Group Structure

This document was prepared by the Working Group co-chairs based on an extensive consultation and engagement process with the Working Group members and formal submissions of input from nearly all participants.

Working Group co-chairs:

- Clean Air Task Force
- Danish Ministry of Climate, Energy, and Utilities (withdrew on 5th October 2022)
- Florence School of Regulation

Working Group members:

- Agora Energiewende
- Air Liquide
- Aker Carbon Capture
- ArcelorMittal
- Austrian Association for Building Materials and Ceramic Industries
- Avenia Pycasso
- Baker Hughes
- Bellona Europa
- Bioenergy Europe
- BP
- Bundesministerium für Wirtschaft und Klimaschutz
- Carbo Culture
- Carbon Clean
- Carbon Engineering Ltd.
- CCSA/Zero Emissions Platform
- CEFIC
- Chevron
- Cimpor
- Climeworks
- CO2 Value Europe
- CO2 Value Australia
- CO2GeoNet
- Communauté d'agglomération Pau Béarn Pyrénées
- DC & P
- DGMK
- DOW
- Drax Group
- EBN
- EERA
- eFuel Alliance
- Energy Policy Group
- Engie Laborelec
- ENI
- Equinor
- ERCST
- ETH Zürich
- EUROFER
- Eurogas
- European Lime industry Association
- Evida
- Fortum Recycling & Waste
- Gassnova
- GE
- Global CCS Institute
- Göteborg Energi and Renova
- Government of Flanders
- Hafslund Oslo Celsio
- Heidelberg Materials
- Holcim
- TES Hydrogen

- INERCO
- IOGP
- KlimaDiskurs.NRW
- LanzaTech
- Margriet Kuijper Consultancy
- MCi Carbon
- Ministry of Economy and Sustainable Development, Croatia
- Mitsubishi Heavy Industries
- Negative Emissions Platform
- Norddanmark EU Konter
- Norsk Hydro
- Northern Lights
- Norwegian Ministry of Foreign Affairs
- Norwegian Ministry of Petroleum and Energy
- Norwegian Petroleum Directorate
- Offshore Energies UK
- Port Rotterdam (Porthos)
- RasmussenGlobal
- Repsol
- RWE Generation SE
- SCHWENK Latvija
- Shell
- SIA partners
- SNAM
- South Pole
- Stiftung Wissenschaft und Politik (SWP)
- Stockholm Exergi
- Swedish Environmental Protection Agency
- The Bioenergy Association of Finland
- The European Lime Association
- Total Energies
- UNIPER
- University of Zagreb
- Verein Deutscher Zementwerke e.V.
- VW
- Wintershall DEA

Additional comments from members

Some of the organisations listed above have not necessarily endorsed the entire document. Additional comments from Working Group members are provided here:

Cefic comments on the document of the CCUS Forum Vision working group include:

- **Proper terminology & definitions** are essential:
  - CCS, CDR (DACS and BECCS), CCU (and related sub-categories) should be used instead of CCUS and the related IPCC definitions should be used.
  - “Decarbonisation” cannot be applied to the industry: while energy carriers can be decarbonised, neither the industry nor the economy can be “decarbonised” as carbon is and will remain an essential element of most products needed by society.
- **Scope: both climate and carbon circularity** (sustainable carbon circles) should be considered for the definition of the policy framework and a proper evaluation of the technological options considered.
- **A common understanding of how to evaluate the impact** (in particular the climate impact) of the various carbon removal, storage and circularity options should be considered as a prerequisite for the design of a European policy framework that can effectively contribute to the Green Deal targets.