A European Strategy for Carbon Capture and Storage

Key policy recommendations for commercialisation of carbon capture and storage and carbon removal and storage technologies

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CLEAN AIR TASK FORCE

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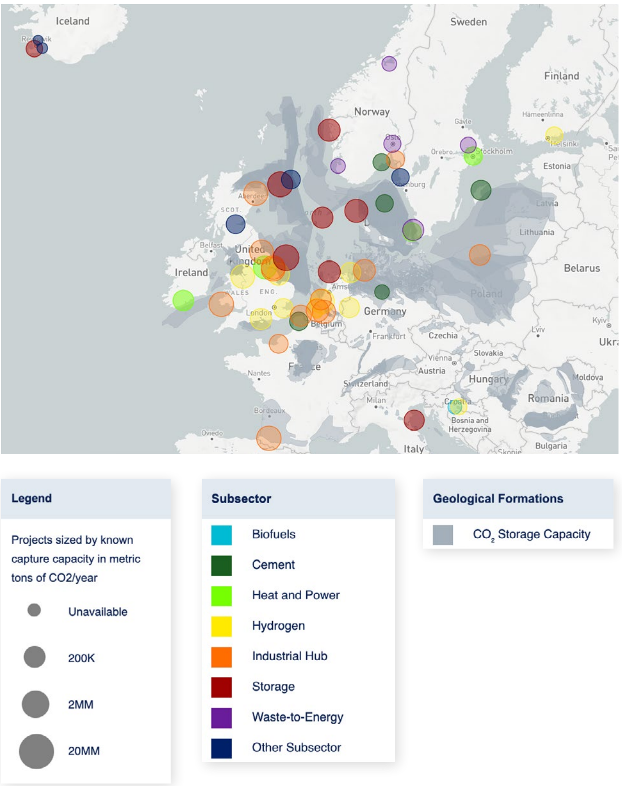
Executive Summary

A critical decade for carbon capture and storage

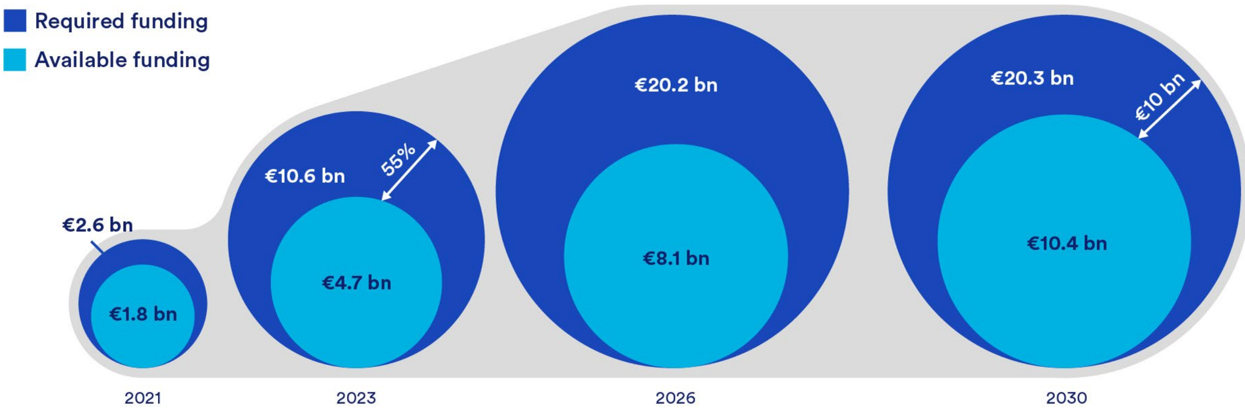
With the advent of legally binding commitments to achieve ‘net zero’ greenhouse gas emissions by 2050 or sooner there has been a marked growth in efforts to deploy carbon capture and storage across in Europe. This concept encompasses the suite of technologies that can capture CO_2 – either from existing emission sources or from the atmosphere – and permanently store it in deep geological formations. Modelling of pathways to net zero highlights the critical decarbonising role for carbon capture and storage across the energy system, in abating industrial and power sector emissions, production of low-carbon fuels, and as a source of permanent carbon removals. However, previous efforts to deploy these technologies at large scale in Europe have struggled, owing primarily to inadequate regulatory incentives and the need to develop common CO_2 infrastructure. Now, with over 50 carbon capture or storage projects proposed across the region (offering an abatement potential of over 80 Mt of CO_2 per year), it is imperative that EU and national governments develop a coordinated policy framework that allows these first-mover projects to progress and develop into a viable, region-wide industry for CO_2 storage.

Planned and operating carbon capture and storage projects in Europe[10]

View the full map here



The gap between announced funding for carbon capture and storage and the funding announced projects require to have a positive net present value (cumulative over time)[84]



Closing the funding gap

Like most decarbonising technologies, carbon capture imposes a cost on emitting industries, including capital costs and ongoing operating costs for CO_2 capture and transport and storage fees. The EU's carbon pricing system should provide an investment signal for emitters to internalise these costs, but it remains a weak and overly volatile driver for most industrial sectors, particularly due to the presence of free allowances. Taking into account the carbon price and existing funding schemes, there is a revenue shortfall for currently announced projects which amounts to a cumulative €10 billion by 2030 (Figure above). This 'funding gap' can be closed at the EU and national level through policies such as 'carbon contracts for difference' which provide a form of guaranteed carbon price for decarbonising projects; such an approach is already being adopted by national governments such as the Netherlands, the UK and Denmark.

Key recommendations:

- Increase the size of the EU's Innovation Fund programme and consider frontloading funding to promote earlier project development
- Introduce new operational subsidies for capture plants at the EU and national level, for example, via a contracts for difference model
- Ensure new and existing funds for industrial decarbonisation funds are accessible to carbon capture and storage

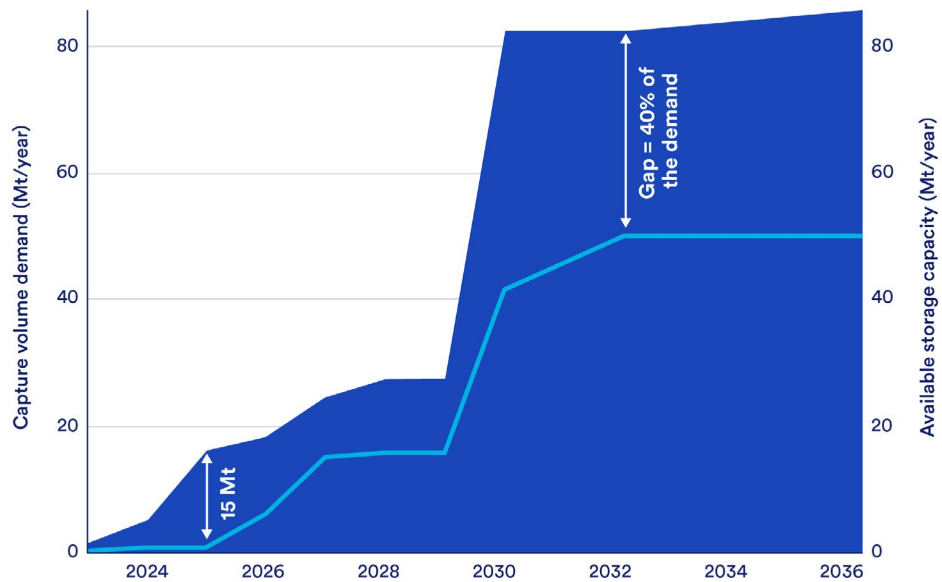
Establishing large-scale, open-access storage

Although the progress of new CO_2 transport and storage projects such as Norway's 'Northern Lights' has catalysed widespread growth in capture projects, the development of geological storage sites is falling far behind demand. Based on currently announced project timelines, there could be a 50% shortfall in developed storage capacity by 2030, and yet, Europe boasts an estimated 500 Gt of theoretical capacity for CO_2 storage (Figure on next page). Storage sites can take several years to develop and permit, rely on detailed geological data, and require risky pre-construction investments, particularly for first-mover projects with uncertain demand.

Key recommendations:

- Public support for the characterisation and development of large-scale stores (>100 $MtCO_2$) on a coordinated, cross-border basis
- Introduce regulatory requirements for the oil and gas industry to undertake steps towards storage site development (including data acquisition and permitting)
- Incentivise industry to reuse existing oil and gas infrastructure for CO_2
- Provide EU guidelines to streamline storage site permitting
- Develop new financial instruments to cover the small risk of CO_2 leakage

The widening gap between volumes of CO_2 captured and available storage, based on current project announcements[85]



Building beyond the North Sea

To date, development of CO_2 storage capacity has been concentrated in the North Sea, where well-characterised geology and existing oil and gas assets present a favourable environment. To ensure Europe's emitting industries have equal access to the decarbonising potential of this infrastructure, it is vital to promote and facilitate the development of other suitable storage geology throughout the region, including onshore storage in Central and Eastern Europe, and offshore storage in the Mediterranean. This process can be effectively accelerated through sharing of technical and regulatory best practice, capacity building within Member State governments, and EU-coordinated efforts to identify and develop promising storage sites.

Key recommendations:

- Promote capacity building initiatives for government and other stakeholders in key Member States
- EU-coordinated efforts to update carbon storage regulations in Member States
- Identify promising, large-scale onshore or offshore storage regions in Southern, Central, and Eastern Europe and ensure they are developed to the point where they are 'injection ready'
- Explore ways in which the Just Transition Fund could be used more broadly to help industrialised regions to access CO_2 storage

Coordinating clusters and common infrastructure

A key enabling characteristic of many of Europe's current wave of carbon capture projects is their separation of the commercial framework for CO_2 capture from that of transport and storage. This model is typical of several 'cluster' initiatives, in which a CO_2 infrastructure operator services emitters within a localised industrial region. While this approach reduces project complexity for emitters and allows for economies of scale, it presents new challenges for policy design, which must move from 'project-by-project' funding to a system-based approach, as well as helping to reduce stranded asset and cross-chain risks.

Key recommendations:

- Enable national and EU funding to use regional synergies and scalability of climate impact as criteria
- Develop risk management strategies and business models which enable the steady expansion of cluster networks

Moving to a market for low-carbon products and services

In the medium-term, a sustainable commercial framework for carbon capture and storage in industry should move from reliance on government support towards a market driven by demand for low-carbon products and services. The relative cost increase in the production of low-carbon raw materials such as steel and cement is less significant when applied to end-use products. Policy can help accelerate this transition by developing low-carbon product certification, setting regulatory standards for end-user products, and seeding initial demand.

Key recommendations:

- Develop rigorous low-carbon product certification
- Implement public procurement of low-carbon products such as concrete and steel
- Carbon intensity limits for end-use sectors such as construction and vehicles
- Set sectoral targets for the adoption of low-carbon products

Driving permanent carbon removals

There is a consensus that large-scale removal of CO_2 from the atmosphere will be required at net zero, both to offset remaining fossil emissions and address any climate 'overshoot' through net negative emissions. The geological storage of atmospheric CO_2 obtained either through direct air capture or processing of climate-beneficial biomass are technological removal solutions that offer high levels of permanence and low leakage risk. There is an important role for policy in establishing rigorous certification mechanisms and introducing funding streams for higher-cost, high-value forms of carbon removal, without compromising efforts to reduce emissions.

Key recommendations:

- Develop a portfolio of removal options for Europe while progressing towards higher permanence solutions
- Ensure the forthcoming EU certification mechanism for carbon removal is based on full life-cycle analysis and minimises uncertainties around permanence and leakage
- Targeted funding mechanisms to support the early development of technological removals
- Set scientifically informed targets for technology-based removals
- Set standards to encourage the use of waste biomass feedstocks and limit new land clearing

A market for low-carbon hydrogen

As fuels currently represent 80% of global energy consumption and many of today's applications will remain difficult to electrify, very large volumes of low-carbon fuels will be required in a decarbonised economy. Using carbon capture and storage to decarbonise the production of hydrogen from natural gas offers a rapidly scalable source of low-carbon hydrogen that can help prioritise renewable energy for power sector decarbonisation. Policy must first ensure the climate impact of all forms of hydrogen is rigorously assessed, and then encourage technology-neutral funding to fuel sources on the basis of decarbonising potential alone.

Key recommendations:

- Establish a robust certification system for low-carbon hydrogen with ambitious thresholds (including upstream emissions) that is adaptive to technology developments
- Eligibility for hydrogen-as-fuel in decarbonisation funding
- Regional planning and coordination of hydrogen networks with CO_2 networks

Addressing barriers to a flexible and international market for CO_2

The ability to move CO_2 across borders is essential in creating Europe-wide access to a portfolio of potential storage sites, enabling economies of scale and reducing individual project risks. Currently, cross-border transport of CO_2 for offshore storage requires bilateral agreements which are time consuming and could lead to a lack of regulatory alignment. The EU and national policy must work to coordinate CO_2 transport regulation and technical standardisation in order foster a flexible and scalable market for CO_2.

Key recommendations:

- Include all transport modalities in the revision of the TEN-T regulation
- Develop a Europe-wide set of CO_2 specification standards for transportation and storage
- Establish a platform for coordination between transport network operators
- Encourage Member States to ratify the London Protocol and establish guidelines for bilateral agreements

Building broad stakeholder support

Some initiatives to deploy carbon capture and storage in Europe have met with opposition, often based on concerns over storage safety and association with the continued use of fossil fuels. Governments can take a leading role in clearly laying out the compelling case for the technology in the context of a transition to net zero, while ensuring new policies are rooted in an open dialogue with civil society, labour unions, industry, and other stakeholders.

Key recommendations:

- Evidence-based messaging from all levels of government on the role of carbon management in reaching net zero
- Support policy announcements with good communication and inclusive stakeholder consultation
- Encourage local governments or other local entities to help coordinate regional clusters

An EU strategy for carbon capture and storage

Carbon capture and storage in Europe is a fundamentally international endeavour, in which Member States must share their CO_2 storage resources, develop new connecting infrastructure, and align their funding and regulatory approaches where possible. As such, the European Union should take a leading position in helping to coordinate and plan this new decarbonising industry, as well as promoting knowledge sharing within the region. Through a dedicated strategy for carbon capture and storage, the Commission can lay out a roadmap for growth on the timescales required by the net zero target. This document would provide a clear signal to those industries and member states intending to use carbon capture and storage to decarbonise that their efforts will be supported.

Strategy points:

- Set clear milestone targets for industrial capture and technology-based CO_2 removals based on scientifically sound long-term modelling and a climate risk minimisation approach
- Develop a plan to identify and develop strategically placed storage sites, based on Member State submissions of prospective capture and storage volumes
- Coordinate relevant EU legislation and EU funding with Member State initiatives
- Establish a position on the appropriate manner of regulation for CO_2 storage to avoid monopoly power, stimulate competition and expansion
- Develop an overarching plan for the development of optimised cross-border CO_2 transport infrastructure, including solutions for dispersed emitters
- Establish a Europe-wide regulatory platform for CO_2 transport infrastructure
- Encourage relevant Member States to ratify the London Protocol amendment and address any regulatory gaps on CO_2 storage
- Create a regional coalition to ensure the North Sea Basin is developed on schedule to deliver on the order of 1 Gt of storage by 2050
- Provide guidelines on how to collaborate and trade CO_2 with non-EU countries
- Establish a dedicated European forum on carbon capture and storage for coordination between industry and other stakeholders, knowledge transfer and commercial engagement

SECTION 1

Introduction

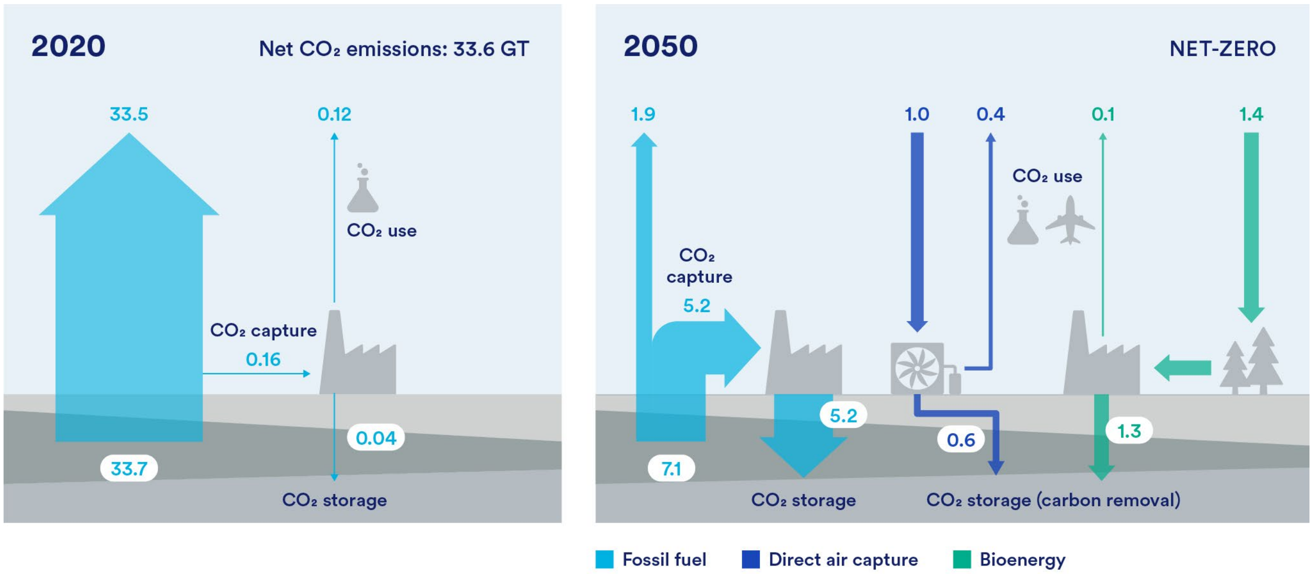
The role of carbon capture and storage for net zero

In response to the urgency of the climate crisis, the European Union (EU) has set a target of achieving 'net zero' greenhouse gas emissions by 2050, with an interim target of a 55% reduction by 2030.[1] Several Member States have implemented their own legally binding plans to reach climate neutrality even faster. As underlined by the International Panel on Climate Change (IPCC), a transition to net zero on such short timescales is necessary on a global level if warming is to be limited to 1.5°C above pre-industrial levels[2], and the EU is well positioned to play a leading role in this international endeavour. But the scale of the task for society is unprecedented and hinges on whether many of the low-carbon technologies which are currently at early stages of development can move to widescale deployment in an exceptionally short timeframe.

Carbon capture and storage and carbon removal, often known collectively as carbon management technologies, are in particular need of such accelerated development. Based on the process of separating CO_2 from industrial emissions – or from the atmosphere itself – and injecting it into porous rock deep below the surface, these technologies are unique in their ability to return carbon to the earth. While a societal transition away from fossil fuels is the end goal, energy system modelling consistently emphasises that these forms of carbon management will be essential in achieving net zero within the necessary timeframe and at lowest cost to society. The IEA's 'Net zero by 2050' scenario includes 7.1 Gt of CO_2 stored per year by 2050 and, across the 18 IPCC '1.5°C scenarios' that also achieve net zero in the energy sector by 2050, an average of 15 Gt per year is ultimately captured and stored.[3]

The pivotal role played by carbon capture and storage technologies in net-zero scenarios relates to the diverse functions it can provide in a decarbonised economy.[4] It offers a means of mitigating CO_2 emissions from 'hard-to-abate' process industries, such as cement, steel, and chemical production where, in some cases CO_2 is unavoidably emitted by chemical processes, or high temperatures are required which are challenging to deliver by electrification. While renewable energy sources will increasingly dominate the power generation sector, in many cases there is a role for carbon capture to decarbonise the dispatchable power plants required to support intermittent wind and solar, as well as for the decarbonisation of recently built fossil power plants.

Figure 1: Carbon capture and storage in the IEA's 'Net zero by 2050' roadmap[3,4]



Carbon capture can also help deliver the enormous quantities of low-carbon fuels, such as hydrogen, which will be needed in a net zero world. Perhaps most importantly, the geological storage of CO_2 derived from direct air capture or some bioenergy processes offers a means of permanently removing large volumes of carbon from the atmosphere.

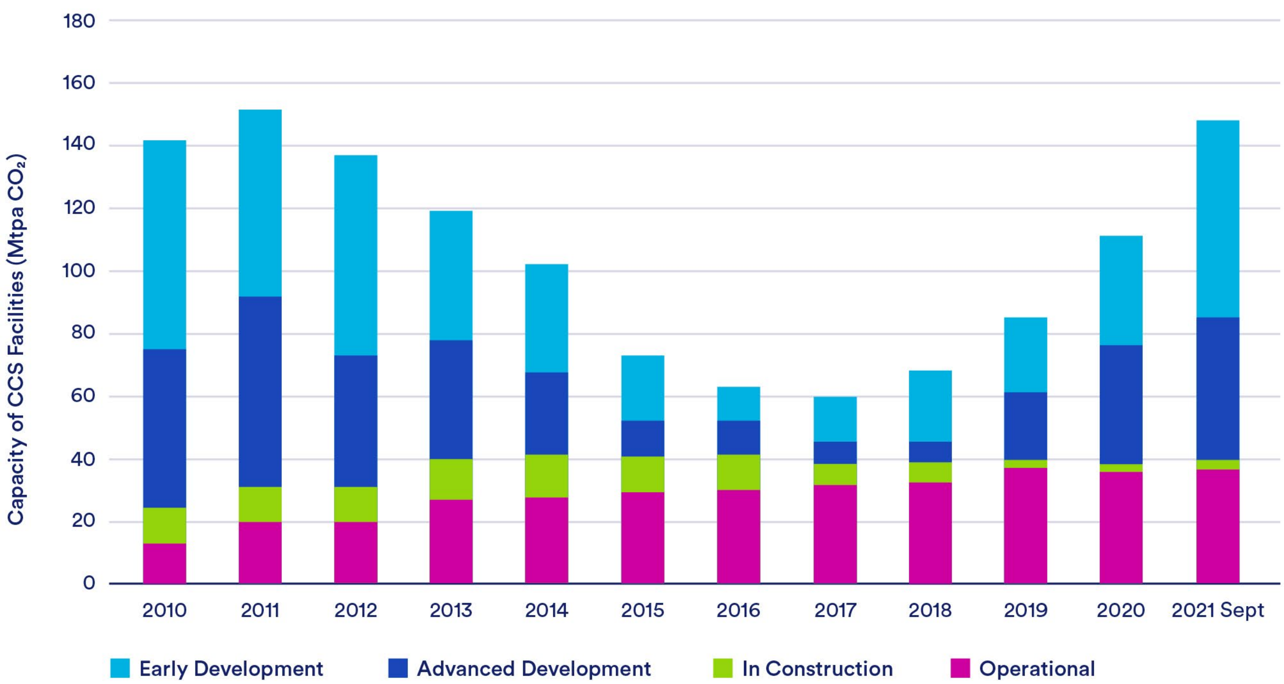
In short, the ability to return carbon to the earth is likely to be of profound utility to society; not as a means of sustaining fossil fuel production, or as a competitor with renewable energy sources, but as a complement to them: to provide the clean steel, cement, and other materials needed for their manufacture, the clean power to back them up, and the alternative sources of hydrogen which can prioritise renewable energy for other uses.

However, despite various political initiatives to address this clear need, the deployment of carbon capture and storage has progressed slowly to date (**Figure 2**), often struggling to move beyond first-of-a-kind demonstration projects or, in some sectors, even to reach this stage.[5] This is particularly evident in Europe, where only two full-scale projects are operating today, out of around 26 worldwide. These operational facilities have nevertheless demonstrated the technical feasibility of carbon capture and storage for a range of applications and showcased its decarbonising potential; the next step is to formulate climate and innovation policies that allow the technology to be implemented at the pace required to reach net zero.

The scale-up of innovative low-carbon technologies requires an end-to-end, holistic policy framework that can create the necessary conditions for growth at each phase of development. Rather than culminating with first-of-a-kind projects, the end goal of low-carbon technology deployment policy should be the widescale use of the target technology.[6] At this level of penetration, technology adoption can be driven by market-based incentives underpinned by appropriate regulatory regimes, such as carbon pricing. This approach requires policies designed to assist new technologies beyond the research, development, and demonstration stages to reach 'n^{th}-of-a-kind' projects – representing the point at which the technology has standardised designs and is 'de-risked' for investors (usually after around 5 to 10 generations) – and finally to enable the rapid expansion of this iteration.

The successful progression of a technology through each development stage also depends on several key 'success factors', including declining technology

Figure 2: The pipeline of commercial CCS facilities from 2010 to September 2021[5]



costs, easy access to finance, time-optimised project deployment, the presence of enabling infrastructure and supply chains, and sufficient public support. Early development stages should have the end goal of widespread deployment in mind, for example, by promoting technologies and projects which are readily scalable, and making use of incentives which are can easily evolve into the support required by later stages. Policy should also aim to move beyond project or technology-centric approaches towards a 'whole system' perspective, in which a range of projects and complementary technologies can share infrastructure and exploit opportunities for circularity. For innovative technologies to move away from reliance on direct public support, policies must establish the business models and regulatory frameworks which can translate a technology's value to system decarbonisation into value for private investors at the project level.

Carbon capture and storage is in clear need of such a comprehensive policy strategy, as previous efforts to drive deployment have struggled with several challenging hurdles, including relatively high upfront costs, often long project lead times, poor public awareness or support, and the need for coordinated development with shared infrastructure. These technologies face the daunting task of moving from first-of-a-kind projects to n^{th} generation plants in the space of a few years, before rapidly transitioning to a more market-led expansion phase. This will require an equally rapid and flexible shift in policy design.

This report puts forward a set of policy recommendations for the acceleration of carbon capture and storage deployment in Europe, with particular attention to the EU. It begins by reviewing the current state of play for the technology across the region, both in terms of near-term project plans and the existing policy and regulatory landscape. Based on extensive engagement with first-mover developers and other stakeholders from industrial sectors, it lays out a series of key themes that must be addressed by forthcoming policy development in the EU, the Member States, and their partner countries in the wider region. Finally, an outline for an overarching strategy for carbon capture and storage in the EU is proposed.

SECTION 2

The status of carbon capture and storage in Europe

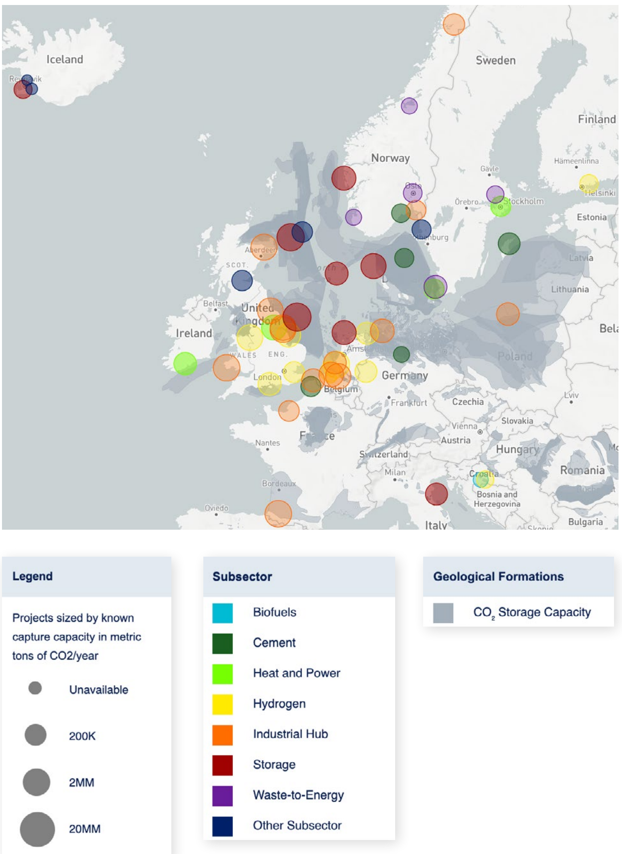
In 1996, Norway's Sleipner gas platform began injecting CO_2 separated from natural gas back under the seabed into a saline aquifer formation, making it the first CO_2 storage operation in the world dedicated to emissions reduction. Driven by Norway's introduction of a high carbon tax for offshore oil and gas operations, this facility was later joined by a somewhat more complex development at the Snøhvit platform in 2008 (including offshore transport of CO_2).[7] Although these pioneering initiatives have remained the only large-scale demonstrations of a complete carbon capture and storage process in Europe to date, they have been pivotal in establishing the potential for safe, long-term storage of CO_2 under the North Sea, and have set the stage for today's developments.

Building on Sleipner's pioneering example, Europe was at the forefront of global efforts to develop carbon capture as a climate change solution in the early 2000s, with a particular focus on applying the technology to coal-fired power plants, owing to their status as Europe's largest point sources of CO_2 and the world's most emitting sector. A G8 meeting in 2008 set a target of launching at least twenty full-scale plants equipped with carbon capture and storage by 2020.[8] To help drive this effort, the EU gave such projects eligibility for its 'New Entrant Reserve' 300 (NER 300) fund, which used sales of allowances in the EU Emissions Trading System (ETS) to finance low-carbon technologies. However, the collapse in the carbon price following the global financial crisis, combined with inadequate financial support from Member States and, in some cases, local opposition to projects, meant that none of the planned facilities were ultimately realised.[9]

Beginning in around 2015, a revival of political and corporate interest in carbon capture deployment in Europe resulted in large part from the more ambitious climate targets associated with the Paris Agreement, and more recently, the target of net zero in 2050 set by the European Climate Law.[1] Today, there are more than 50 proposals for carbon capture and storage projects in the region (**Figure 3**).[10] This new wave of interest in the technology is characterised by two key differences with the efforts made earlier in the century. First, a shift from coal power applications to a focus on emissions from

Figure 3: Planned and operating carbon capture and storage projects in Europe[10]

View the full map here

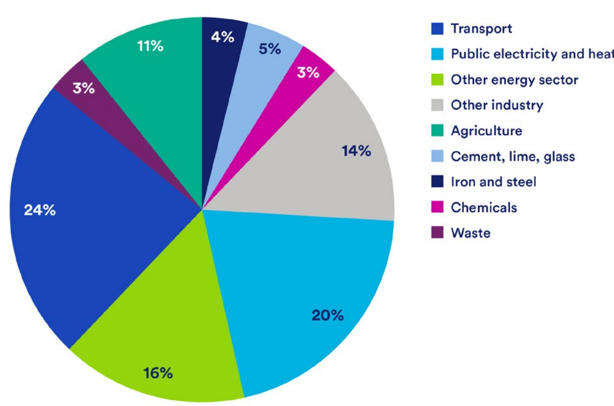


industries with few alternatives to decarbonise such as cement, chemicals, and steel (**Figure 4**), as well as, in some countries, decarbonising hydrogen production and gas-fired power plants. Second, there is widespread recognition that the localised, emitter-oriented business of capturing CO_2 must be addressed separately from the economic challenge of developing transport and storage infrastructure which can be shared by several sources of CO_2.[7,11,12] This approach aims to avoid the failures of the past, in which projects led by single large emitters were often ill-equipped to take on the technical challenges, high costs, and project risks associated with the development of 'common carrier' infrastructure and geological storage. The separation of the economic model for project infrastructure can encourage sufficient transport and storage capacity to be deployed to service multiple emitters, allowing for economies of scale and the sharing of project risks over multiple sites.

Current proposals for shared CO_2 infrastructure are mostly based around highly industrialised areas where 'clusters' or 'hubs' of emitters such as refineries, chemical plants, steel plants and power plants can share a common CO_2 trunk pipeline – this is typified by the Porthos project in the Port of Rotterdam and the UK initiatives including the East Coast Cluster and HyNet (**Figure 5**). However, a related model, most notably adopted by Norway's 'Northern Lights' project, is to collect CO_2 from widely dispersed, coastal emitters using CO_2-carrying ships. Much of this drive to develop service-oriented, open-access CO_2 storage infrastructure has featured oil and gas companies, including Equinor, Shell, Total, Eni and BP, which have the appropriate geological expertise, existing offshore assets, and are also increasingly driven by their own corporate pledges to achieve net zero emissions (usually confined to Scope 1 and 2 emissions).[14]

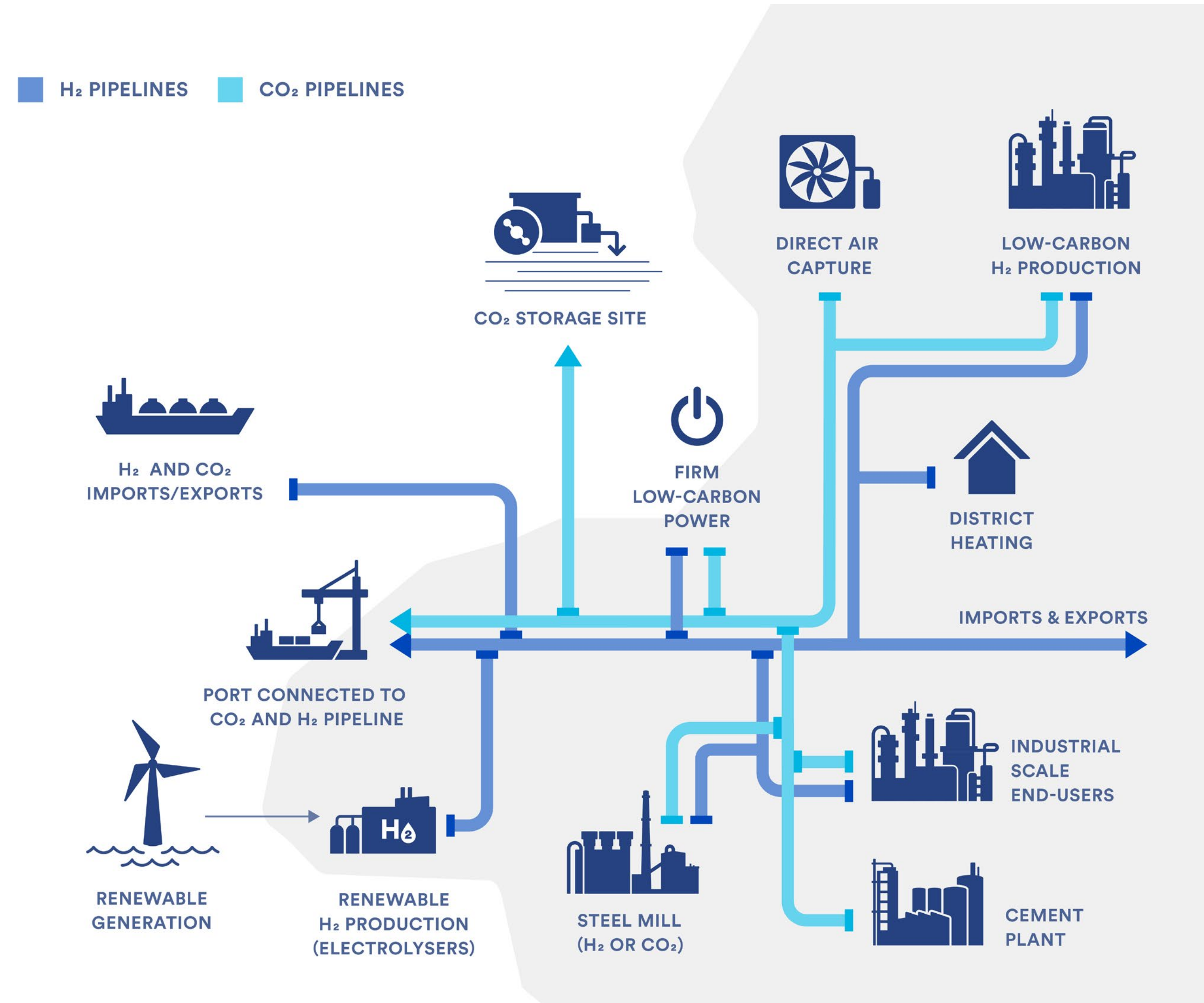
Boasting over 150 Gt of total theoretical storage capacity, in both saline aquifers and depleted gas fields, the North Sea has become the focus of carbon capture activity in the region, with the result that the vast majority of planned projects are located in the UK, Norway, and the Netherlands, as well as more recent proposals in Northern France, Belgium, Denmark, and Sweden.[15] Many clusters and individual emitters on the North Sea and Baltic coast have declared an interest in using ship-based transport to connect to the various storage sites proposed, demonstrating the catalytic effect that this transport solution has had by offering a more flexible, lower capital decarbonisation proposition to coastal industries. Elsewhere, Eni's Ravenna Hub proposal in Italy and Energean's project in Greece are based on storage in depleted gas fields in the Mediterranean.[16,17]

Figure 4: Emissions by sector for the EU27 and the UK in 2019[13]



Although the continent also has ample onshore storage geology and several large-scale trials have been completed, interest in this route has been heavily muted following strong local opposition to some earlier proposals in the Netherlands and Germany. Examples of onshore proposals include the Pycasso project, based on storage in depleted gas fields in South-Western France, and two initiatives in Croatia which plan to exploit depleted oil and gas fields.[18,19]

Figure 5: Decarbonisation of an industrial cluster using carbon capture and storage and hydrogen networks



SECTION 3

The existing regulatory and policy landscape

EU policy instruments

A key prerequisite to CO_2 storage in Europe is the EU's directive on the geological storage of CO_2 – widely known as the 'CCS Directive' – which was introduced in 2009 and made law in most Member States by 2011.[20] This directive establishes the rules around appropriate selection of CO_2 storage sites, and the operation, closure and post-closure obligations for site operators. A significant provision is its allowance for the transfer of liability from the site operator to the national government after a minimum of 20-30 years following the completion of CO_2 injection, provided the operators can demonstrate the store is stable and intact. Although not all legal and liability-related issues are solved by the directive, it has set a solid base on which early project development can proceed. However, Member States have considerable flexibility in how they choose to implement the directive, with Germany effectively limiting CO_2 injection to pilot projects, and countries including Austria, Latvia, Lithuania, Slovenia, and Finland prohibiting CO_2 storage outright.[21]

Fundamentally, carbon capture and storage imposes a cost on emitting industries and it will therefore not see widespread implementation unless that cost can be recouped through additional revenue or internalised due to regulation. Under the 'split chain' model described above, an emitter is generally responsible for purifying CO_2 to a given standard and pays a separate transport and storage operator to take the CO_2. While this simplifies the project structure for the emitter, the combined costs of both the capture process and the transport and storage tariff must be supported by equivalent income streams. In the EU, the principal driver for decarbonisation activity in the power and industrial sectors is the carbon price under the ETS, which imposes an additional cost on most emitting industries. In theory, the avoidance of these costs through carbon capture can represent a positive investment case to emitters. However, in practice, the additional costs of the process must still be recouped – potentially by passing costs onto customers. The incentivising effect of the ETS is further complicated by the existence of free emission allowances for most manufacturing industries, which are aimed at mitigating the potentially damaging effect of high carbon prices on the global competitiveness of European export goods. These are allocated based on each industry's carbon intensity and exposure to trade, together with benchmark emissions from the sector's most efficient installations.

Although the carbon price reached record levels of nearly 100 €/t in January 2021 (**Figure 6**)[22], its subsequent rapid fall illustrates the difficulty in relying on this signal alone when making capital-intensive investments. While the price is expected to trend upwards in the long term (in accordance with the EU's climate goals), in the near term it remains too low and unpredictable for driving investment in many of the decarbonisation technologies which will be necessary to reach net zero – particularly those which require supporting infrastructure like carbon capture and storage. Consequently, most current project proposals in the region have sought to obtain additional streams of funding, either from national governments or through other EU funds.

Figure 6: The price of CO_2 allowances in the EU ETS (€/t) over the past 10 years[22]

At the EU level, the most significant of these is the **Innovation Fund** – a scheme that follows the NER 300 format by using proceeds from the sale of EU ETS allowances to support innovative low-carbon technologies.[24] Over a ten-year trading period starting in 2021, the scheme will sell 450 million allowances, which – assuming a carbon price of €50 – would raise around 25 billion euros to be awarded evenly over annual calls to 2030. The total size of the fund could increase significantly if the ETS price remains high. In 2020, over 300 projects (including over 60 with an element of carbon capture and storage) applied for 1 billion euros earmarked for large-scale projects; however, only seven projects were ultimately successful, of which four included carbon capture and storage (**Table 1**).[23] The Innovation Fund is notable for providing successful projects with support for up to 60% of additional capital and operating costs.

Under a current proposal to revise the EU ETS, there is also a proposal to increase the scope of the Innovation Fund with the addition of 200 million allowances, as well as a portion of the 'free allowances' that will no longer be provided to industry.[25] A portion of the fund may also be allocated on the basis of carbon contracts for difference (*see explanatory box*).

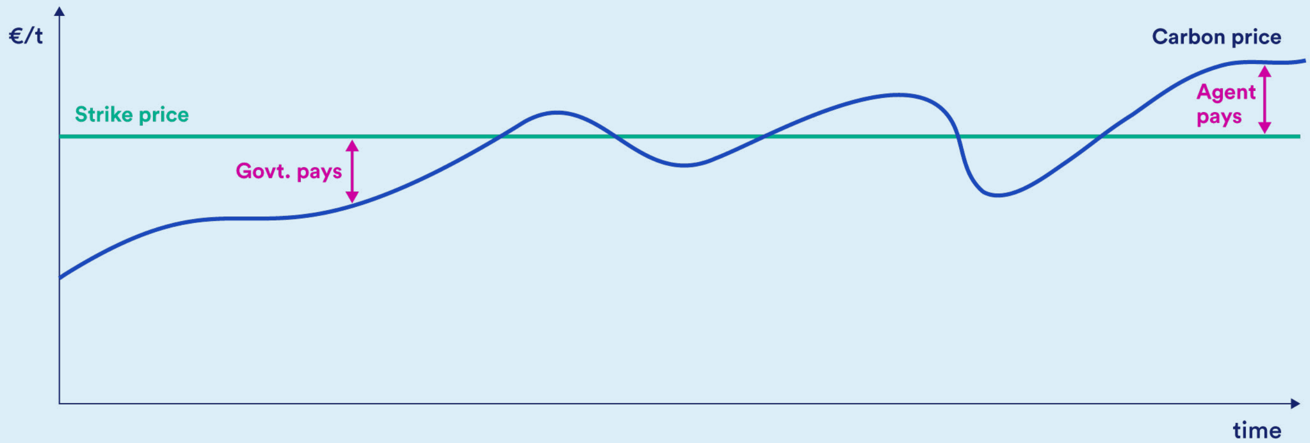
Table 1: Projects selected by the first Innovation Fund call for large-scale decarbonisation projects (2021)[23]

Project	Location	Developers	Description	Maximum grant (€)	€/t CO_2 avoided
Kairos@C	Antwerp, Belgium	Air Liquide Large Industry SA, BASF	14.2 Mt/year CO_2 captured from 5 emitters in the Port of Antwerp (2 hydrogen plants, 2 ethylene oxide plants, 1 ammonia plant) and CO_2 shipping vessels for storage in the Netherlands, Norway, or the UK. Linked to transport infrastructure developed by Antwerp@C consortium.	356,859,000	25.1
K6	Pas-de-Calais, France	Eqiom, Air Liquide France Industries	CO_2 reduction and capture (via an oxyfuel process) from Eqiom's Lumbres cement plant in Northern France. CO_2 will be transported to Dunkirk for onwards shipping to North Sea storage.	153,386,598	18.9
Stockholm Exergi BECCS@ STHLM	Stockholm, Sweden	Stockholm Exergi	Capture of 800 kt/year CO_2 from a biomass-fired combined heat and power plant with the aim of achieving net carbon removals. CO_2 will be transported by ship for storage in Norway.	180,000,000	23.1
SHARC	Porvoo Refinery, Finland	Neste Oyj	Sustainable Hydrogen and Recovery of Carbon. Includes production of hydrogen from water electrolysis (50 MW scale) and from methane with carbon capture and storage.	88,286,266	22.1

Carbon contracts for difference

Carbon contracts for difference (CCfDs) form the basis of many current proposals to provide an investable revenue stream for decarbonisation projects in industry, including carbon capture and storage. This model is aimed at providing a higher and more predictable carbon price signal to investors in decarbonisation technologies which are still too costly to be driven by current CO_2 prices.[26] A government or other contracting party agrees on a carbon 'strike price' (on a € per tonne of CO_2 basis) with the project operator, either through bilateral negotiation or a competitive process. The government then pays the operator the difference between the actual carbon price and the strike price for any emissions reductions achieved; these reductions may have to be calculated relative to a benchmark 'business-as-usual' value (**Figure 7**). If the carbon price should go above the strike price, the emitter must pay this excess back to the government.

Figure 7: Carbon contracts for difference[26]



The model is similar to Contracts for Difference (CfD) used to promote low-carbon electricity in the UK, where the strike price is instead set per MWh of generated electricity.[27] The generator is then paid the difference between the strike price and the wholesale power price for all electricity generated, guaranteeing an income sufficient to cover costs and meet a reasonable rate of return. The success of this approach in accelerating deployment and associated cost reductions of renewable sources – particularly offshore wind – has led to a steady reduction in strike prices, and therefore in the level of government subsidies required.[28] While bilateral negotiation has been used for setting strike prices for some early-stage technologies, competitive bidding processes are later employed to help drive down costs.

The UK's familiarity with CfD support for low-carbon energy has made a form of carbon CfD a popular choice for driving industrial carbon capture deployment in the country, with likely adoption as a technology-targeted revenue model from 2022.[29] The Netherlands' SDE++ subsidy model for decarbonisation technologies (including carbon capture) closely resembles the approach, but is not strictly speaking a contract for difference mechanism, as the project operator does not pay the government back should the market carbon price exceed the 'strike price'; instead, there is a fixed lower limit on the subsidy.[30] The EU has proposed using a form of CCfD for allocation of an expanded Innovation Fund from 2022, and Germany has also announced a CCfD scheme. More recently, Denmark has indicated that a similar model will be used for a forthcoming subsidy scheme for carbon capture and storage (*see section on Denmark*).

The **Connecting Europe Facility (CEF)** is another European initiative which aims to promote shared infrastructure projects throughout the region, through various means of financial support such as grants, loan guarantees and project bonds.[31] Energy and CO_2-related infrastructure projects are able to access this support by obtaining the status of a 'project of common interest' (PCI), with eligibility rules laid out by the 'TransEuropean Network – Energy' or 'Ten-E' regulation.[32] Previously, several CO_2 infrastructure projects have obtained PCI status, accelerating permitting processes and giving them access to the CEF – used primarily for feasibility and front-end engineering and design (FEED) study work; however, support has thus far been limited to CO_2 pipelines and associated equipment (**Table 2**). A 2021 revision of the TEN-E regulation has extended the criteria to include CO_2 storage sites, but did not adopt a proposal by the European Parliament to make CO_2 transport via ships, road, and rail eligible for funding.[33]

The EU has a number of other funding streams which can or have been directed towards carbon capture and storage activity. In particular, many research-based projects have been funded through programmes such as **Horizon 2020** and its successor scheme **Horizon Europe.**[37] In response to the severe economic impact of the Covid-19 pandemic, the EU introduced its stimulus package known as the **Recovery and Resilience Facility**, comprising €723.8 billion in loans and grants to support reforms and investments in Member States.[38] At least 30% of these funds are intended to be directed towards climate-related projects, with several countries including carbon capture and storage activities in their plans submitted to access the funds. **The Just Transition Fund** (JTF) is another key element of the Green Deal, which aims to alleviate the social and economic costs associated with a move to a green economy and directs support to regions with a strong dependence on fossil fuel activity (such as coal mining regions). The JTF has a total budget of €17.5 billion.[39]

Lastly, carbon capture and storage is also included in the **EU's Sustainable Finance Taxonomy**, which defines a list of environmentally sustainable economic activities for investors and project developers, thereby setting the guidelines for any lending in the region labelled as 'sustainable finance' (no funding is associated with this designation).[40]

The role of net zero targets

Enacted in June 2021, the European Climate Law lays out the legally binding requirement for the EU to achieve climate neutrality, i.e., net zero greenhouse gas emissions by 2050, as targeted by the EU's Green Deal in 2020.[1] It also includes an intermediate target of reducing greenhouse gas emissions to at least 55% of 1990 levels by 2030. Some Member States and other countries in the region had already established their own legally binding net zero targets, including the UK, France, and Denmark, which all set 'net zero by 2050' targets in 2019, and Sweden, which pledged in 2017 to reach net zero as early as 2045. In 2021, Germany also set a target of climate neutrality by 2045.[41] In addition to these national targets, several sub-national regions and municipal authorities have also set net zero targets – often on an accelerated schedule relative to the national goal.[42]

Net zero emissions targets play a significant role in shaping climate technology policy, often emphasising and clarifying the need for carbon capture and storage as a complement to other emissions reduction technologies. This can lead to policy changes in how incentives and subsidies for technology development are allocated. Such targets can also have a direct influence on emitting industries, whose long-term strategies

Table 2: List of cross-border CO_2 network PCIs and associated funding from the CEF[34,35,36]

Description	3rd PCI list (2017)	4th PCI list (2019)	5th PCI list (2021)
CO_2 transport infrastructure for the Teesside industrial cluster, UK.	**Teesside CO_2 hub**		
Transport infrastructure for the Acorn carbon capture and storage project, UK, potentially connecting to Netherlands and Norway.	**CO_2 Sapling** €374,138 for a feasibility study on transport infrastructure and €2.8 m for pre-project engineering Norway.	**CO_2 Sapling** €7.9 million for cross-border pre-project engineering	
CO_2 transport infrastructure to connect the Port of Rotterdam, Port of Antwerp, and the North Sea Port	**The Rotterdam Nucleus** €6.5 m to Porthos project	**CO_2 TransPorts** Porthos CO_2 transport network (€102 million for construction); Studies for Antwerp CO_2 collection network and cross-border pipeline (€5.8 million)	**CO_2 TransPorts**
Collection of CO_2 by ship from various European capture plants for storage in Norway	**CO_2 cross-border transport connections**	**Northern Lights** Antwerp liquid CO_2 export terminal (€3.2 million)	**Northern Lights** €4 million towards FEED study for expansion phase (to 5 Mt CO_2 per year)
CO_2 transport and storage from industry and power in Cork, Ireland		**Ervia Cork CCUS Project** €1.4 million euro grant for pre-FEED study	
Infrastructure to transport CO_2 in the Amsterdam-IJmuiden area		**Athos** €15.4 million	**Athos** On hold due to cancellation of IJmuiden steel project
CO_2 transport system to link to a Rotterdam hub for offshore storage in the Northern Netherlands			**Aramis**
A multi-modal CO_2 export hub from Dunkirk and hinterland			**Dartagnan (Dunkirk)**
A multi-modal CO_2 export hub from Gdansk and hinterland			**Gdansk (Poland EU CCS interconnector)**

must plan for a future in which their business remains both viable and a net zero emitter. For industries which are largely reliant on carbon capture for emissions abatement, including cement, lime, and waste to energy plants, net zero targets have had an accelerating effect on plans for demonstrating this technology at scale (*see boxes on Waste to Energy and Cement*). Even without full exposure to the carbon price or receipt of subsidies for carbon capture and storage, some industries may still perceive a strategic need to develop the technology to retain future viability – envisaging a future in which a low-carbon product or service will necessarily carry a higher value.

National activities and policies

The Netherlands

With the Innovation Fund still in its early stages (and CEF funding largely covering feasibility studies for CO_2 transport infrastructure), most early-mover carbon capture projects are being driven by incentives at the national level, particularly in countries around the North Sea where the technology's role in reaching net zero has been recognised in policy. In the Netherlands, the Sustainable Energy Transition scheme (Stimulering Duurzame Energietransitie, or SDE) for supporting renewable deployment was expanded in 2020 to include other carbon reduction technologies – including carbon capture and storage. 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.[43] 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.

Of 4.76 billion euros awarded in the 2020 round of the SDE++, bids for funding CO_2 capture and storage from four emitters associated with the Porthos infrastructure project were successful in securing a guarantee of up to 2.1 billion euros (*see box on Porthos*). However, at current carbon prices, the actual level of funding required over the duration of the contracts would be substantially smaller. A volume cap on the share of subsidies available to carbon capture projects was initially imposed through the 2019 Climate Agreement, at a maximum of 7.2 Mt CO_2 per year for industry and 3 Mt per year for power generation.[44] This was since raised by the interim government to a total volume of 9.7 Mt per year for industry, leaving 7.2 Mt to allocate, once the 2.5 Mt for Porthos is accounted for. Carbon capture projects represent the majority of applicants to the 2021 round of the scheme, with eleven applicants and an average carbon avoidance cost of only 75 €/t; at current ETS price levels, this would not represent a subsidy.[45] The total annual budget earmarked for the SDE++ scheme varies; it was €5 billion in 2020, but the government has announced its intention to raise it to €11 billion in 2022.

Some other carbon capture clusters and storage sites have been proposed in the Netherlands, including emitters in the North Sea Port – a cross-border port region shared with Belgium (*see case study on Carbon Connect Delta*).[46] And 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 project.[47] This site would be fed by a pipeline from Rotterdam, initially sized at 5 Mt CO_2 per year, but gas fields in the region are thought to have a total capacity of over 1 Gt.

Norway

The Norwegian government has long demonstrated strong support for carbon capture and storage and in 2005 established Gassnova, a dedicated state-owned enterprise for overseeing research and driving full-scale deployment. However, significant state backing for a large project was not secured until 2020, when the Norwegian government committed €1.6 billion to the 'Longship' CCS project.[49] The majority of this funding is aimed at the 'Northern Lights' CO_2 transport and storage component of the project led by Equinor, Total, and Shell, which plans to bring CO_2 by ship to a location on Norway's west coast, from where it will be piped to an offshore storage location with an initial capacity of 1.5 Mt CO_2 per year (**Figure 9**). Longship also incorporates two capture plants: Norcem's Brevik cement plant and the Klemetsrud waste-to-energy plant in Oslo, that would both contribute around 400 kt per year of CO_2 to the storage site. The government's funding commitment covers both capital and operational costs of CO_2 capture at the cement plant for ten years, while partial support for the waste-to-energy facility is contingent on the project securing additional funding; however, following a change of ownership, this will be provided by the City of Oslo and new investors. The state funding is estimated to meet roughly three quarters of the total project costs across the three components. Construction at the onshore CO_2 terminal and the Brevik cement plant began in 2021.[50]

Project case study: Porthos

Porthos is a joint initiative of the Port of Rotterdam Authority, EBN (a state-owned gas company), and Gasunie (an energy network operator), to develop shared CO_2 transport and storage infrastructure in the Port of Rotterdam area (**Figure 8**). It will store captured CO_2 in depleted gas fields only 21 km off the Dutch coast, making use of a pipeline with a total length of 55 km.[48]

Originally proposed in 2017, the developers identified four key emitting industries in the port area: two oil refineries owned by Shell and ExxonMobil, and hydrogen production plants owned by Air Liquide and Air Products, which will act as the initial emitters to supply a total of 2.5 Mt CO_2 per year into the network. These facilities represent suitable first-mover capture projects, as they include process gas streams from which CO_2 can be isolated at relatively low cost. In 2020, the initiative was granted PCI status and awarded €102 million from the Connecting Europe Facility, due to its partnership with neighbouring carbon capture cluster plans in Antwerp and North Sea Port. In 2021, the four emitters secured up to €2.1 billion in funding through the Netherlands' SDE++ scheme, which was essential for the commercial viability of the infrastructure project. Part of this funding will cover the tariff which the emitters must pay the Porthos project operators for CO_2 offtake. The project is currently going through the permit application process and a final investment decision is expected in early 2022, with the aim of commencing operations in 2024.

Figure 8: The Porthos CO_2 transport and storage infrastructure[48]

Figure 9: A proposed network of emitters which could feed into Northern Lights (including 'reciprocal storage sites' in the UK and Ireland)[51]

This commitment to the Northern Lights storage project has led to the emergence of several other plans for carbon capture clusters around Norway and beyond. A key requirement of state-support for Northern Lights was its ability to expand beyond the initial projects, and even beyond the capacity of the first phase pipeline, by sourcing CO_2 from emitters around Europe.[51] Provided sufficient CO_2 can be secured, the project intends to expand to a second phase of 5 Mt per year. Plans for capture plants in Norway itself can source funding from various government schemes, including funding for large-scale energy-based projects provided by Enova (a state enterprise tasked with developing cleaner energy technologies), as well as Gassnova's CLIMIT research programme. Norway has also announced plans to introduce a new tax on CO_2 emissions which could reach €200/t by 2030; this would act to top up the ETS for those sectors subject to the EU scheme (not exceeding €200/t in total), but would also apply to other emitting sectors.[52]

The United Kingdom

The UK has also gone through several cycles of government support for large-scale deployment of carbon capture and storage, mostly structured around competitive funding processes between project bids. In 2015, industry confidence was severely dented by the cancellation of a £1 billion fund earmarked for two finalist projects (Peterhead and White Rose). However, in the wake of this U-turn, several regional industrial areas continued to develop decarbonisation strategies based on carbon capture, in some cases planning to make use of offshore storage sites characterised during previous initiatives. In November 2020, the government set a target of realising two of these carbon capture and storage clusters by 2025, and a further two by 2030, backed by a renewed commitment of £1 billion known as the Carbon Capture and Storage Infrastructure Fund (CIF).[53] Primarily aimed at supporting transport and storage infrastructure, this can also be used to fund capital investment in capture projects in more challenging industrial sectors. In a 'Net Zero Strategy' document released in October 2021, the government further increased its ambition to achieving 20-30 Mt of CO_2 storage per year by 2030 (including 6 Mt per year from industry), and at least 50 Mt by the mid-2030s.[54] This came in response to advice provided by the independent 'Climate Change Committee' which informs on binding national carbon budgets at five-yearly intervals.

Alongside the capital grant funding provided by the CIF, the Department for Business, Energy and Industrial Strategy (BEIS) is currently finalising the development of new business models to establish a long-term investment case for a new CO_2 industry. CO_2 transport and storage will be operated as a regulated industry under a regulated asset base (RAB) model, in which the private sector (typically oil and gas companies) builds infrastructure and then charges a regulated tariff to CO_2 suppliers to cover investment costs and a set rate of return.[55] On the capture side, industrial emitters would be compensated via a contract for difference mechanism, in which the government (through an independent counterparty) pays the difference between the carbon price and an agreed 'strike price' which should cover the capture project costs (**Figure 10**).[29,56]

The UK is unusual in the region for identifying a clear role for carbon capture with utility power plants (either gas or biomass-fired) in order to deliver dispatchable, low-carbon power. Power plants will make use of a modified version of existing contracts for difference used for low-carbon power generation, where the shortfall between the wholesale electricity price and a strike price is paid. Known as a 'Dispatchable Power Agreement', the mechanism is likely to also include a payment to cover some fixed costs, in recognition of these plants' role as flexible backup to variable renewable output.[57] A fourth model is currently under development for compensating low-carbon hydrogen production, with the government indicating this will also take the form of a contract for difference based on hydrogen sales.[58] Companies would be compensated the difference between an agreed strike price and the actual 'achieved sales price' per MWh of hydrogen sold, provided the sales price does not fall below the price of natural gas. All these business models for capture plants are envisaged to provide contracts for 10 to 15 years of operation.

A phased system has been implemented to determine the recipients of both the CIF and the operating contracts.[59] In Phase 1, a competitive process was used to identify two clusters with the ability to rapidly implement capture,

Figure 10: The proposed structure for Industrial Carbon Capture projects in the UK[56]

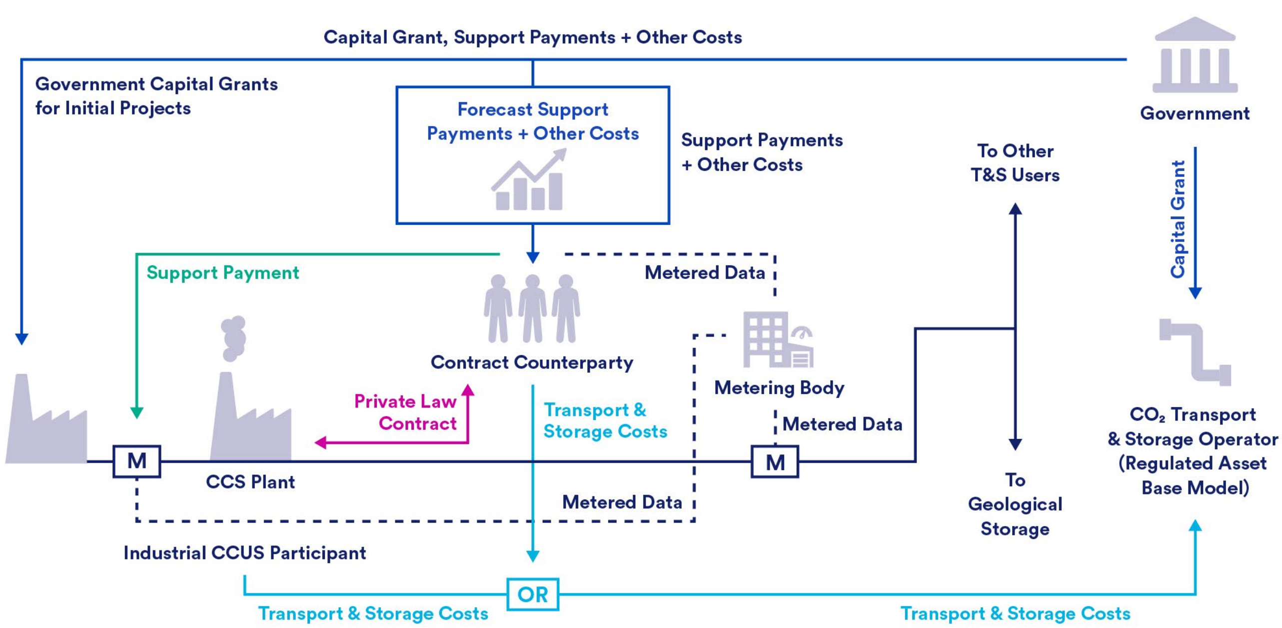


Table 3: A comparison of Dutch and UK support mechanisms for carbon capture in industry

Scheme	Description
UK ICC contract	• 10 or 15-year contract • Reference carbon price follows a straight-line trajectory (derived from UK ETS) • Bilateral negotiation of strike price • Capex payments for first five years (potential for extension) • Free allowances are forfeited at pre-determined price and volume • Payments based on tonnes of CO2 captured and stored • Transport and storage tariff uses a regulated asset base model
SDE++	• 12 or 15-year contract • Reference carbon price is the EU ETS • Competitive bidding for strike price (max rate set for each technology) • Capex support included • Value of free allowances are subtracted from subsidy at market carbon price • Payments based on tonnes of CO2 avoided • Transport and storage tariff incorporated in base rate (maximum bid), based on Porthos cost

transport, and storage at large scale by the mid-2020s. In October 2021, a process to identify first-mover 'Track-1' clusters settled on the East Coast Cluster, representing a combination of two distinct industrial regions in the Teesside and Humber areas feeding into the same offshore store (*see case study on the East Coast Cluster*); and the HyNet project in Merseyside, based primarily on the production of low-carbon hydrogen.[60] Clusters were assessed on a number of criteria, including ability to start operations on schedule, levelised cost of carbon abatement, job creation and economic value, and potential for expansion.

Currently underway, Phase 2 sees emitters within each cluster competing to be the first to connect to these CO_2 pipeline networks. Although the applications or 'cluster plans' submitted to Phase 1 also include a selection of likely emitters, this process is intended to allow other emitters in the region to offer potentially better value decarbonisation. Details for progressing a second stage of 'Track 2' clusters are yet to be announced, but aim to allow for start-up from 2027 in order to meet the national targets for CO_2 storage.

The UK approach is distinctive for attempting to formally structure funding support around the geographical constraints of CO_2 transport and storage infrastructure: the selection of the overall best-value clusters takes precedence over individual emitters. It should also be noted that the government has made no commitment on how the CIF might be apportioned between Track 1 or 2 cluster infrastructure or associated emitters, stipulating that in some cases no grant support may be deemed necessary.

Denmark

Despite previously prohibiting the storage of CO_2, Denmark recently joined the ranks of North Sea countries with a firm commitment to deploy carbon capture, utilisation and storage, following a 2020 Climate Act which set a binding target of 70% greenhouse gas reductions by 2030 (relative to 1990 levels).[61] Accompanying this legislation, a climate agreement for energy and industry set a sectoral goal to reduce annual emissions by 3.4 Mt CO_2 in 2030, of which 0.9 Mt is expected to be achieved through carbon capture technologies. In order to fund the deployment of carbon capture and storage, the agreement also signalled an intention to create a dedicated funding pool of DKK 16 billion (€2.14 billion) over 20 years, with annual allocations increasing from DKK 202 million (€27 million) in 2024 to DKK 815 million (€105 million) by 2030.[62] Also in 2020, the country agreed to halt all oil and gas extraction in the North Sea by 2050 and set aside a further DKK 200 million (€27 million) to support CO_2 storage development, to be allocated through the existing Energy Technology Development and Demonstration Programme (EUDP).[63]

In 2021, the Danish government released a comprehensive carbon capture and storage strategy in two parts.[64] The first part identified various regulations and permitting procedures which would need to be amended or developed, as well as allocating funds towards the characterisation of potential storage sites. The second release primarily addresses how the DKK 16 billion funding pool ('the CCUS fund') will be allocated to projects on a competitive basis, with an initial focus on awarding a single contract for a minimum of 0.4 Mt/year of CO_2 capture and storage by 2026 (this can be though aggregating several emitters). The Danish Energy Agency has outlined that it is considering funding based on a 20-year-duration contract for difference, in which the successful bid price will be adjusted each year according to the average carbon price.[65] The contract will likely be awarded through an open-book negotiation with pre-qualified bidders, using criteria such as project maturity and potential for additional CO_2 capture (over 0.4 Mt/year) in addition to the bid price. The successful project must deliver the complete value chain of capture, transport, and storage, potentially by working with subcontractors of these services. The contract process is expected to conclude by December 2022 and will be followed by a second phase of funding.

The announcement of these support measures has prompted several project proposals related to both capture and storage infrastructure in the country. A consortium led by INEOS has proposed the Greensand storage project based on an offshore depleted gas field (*see project case study on Greensand*), while a consortium led by Noreco and TotalEnergies are seeking to develop another gas field region into a storage site known as Bifrost. In December 2021, these initiatives received total funding of DKK 272 (€36 million) through the EUDP, representing a significant expansion of the original allocation under the North Sea agreement.[66] A number of proposals for capture projects have also been put forward, including the 'C4' consortium of Copenhagen utilities (*see box on waste to energy*) and Aalborg Portland Cement in North Jutland.

Sector case study: Waste to Energy

A significant proportion of early capture project proposals across Europe is represented by waste-to-energy facilities, which use the combustion of municipal waste to generate power and, in many Northern European countries, can also provide steam for district heating. Although this sector represents a relatively small proportion of Europe's industrial emissions, it is at the forefront of carbon capture development for several reasons. Many of the municipalities that own these facilities have made their own commitments to reach net zero – often in shorter timeframes than their national governments – and waste-to-energy plants can represent their single largest source emissions, with little alternatives to carbon capture for abatement. Privately operated plants typically have long duration contracts, allowing for long-term investment decisions.[67] As roughly 50% of the waste incinerated by these facilities is usually of biogenic origin, there is also a potential opportunity to secure revenue through corporate demand for 'negative emissions' credits (*see Driving permanent carbon dioxide removals on page 41*).

Waste-to-energy plants, together with biomass-fuelled combined heat and power plants (which share some of the same drivers) form the major part of the Copenhagen Carbon Capture Cluster or 'C4' initiative in Denmark.[68] A collection of public utilities in the municipality grouped together in 2020 to explore routes to developing common CO_2 infrastructure, with the aim of capturing up to 3 Mt of CO_2 per year. At the heart of the project is ARC's Amager Bakke plant, where a small capture pilot was already commissioned in 2020 and plans for full-scale capture hinge on securing a portion of the EU's Innovation Fund. An advantage of deploying carbon capture in district heating plants such as these is that waste heat generated by CO_2 compression can be used to heat water for the system.

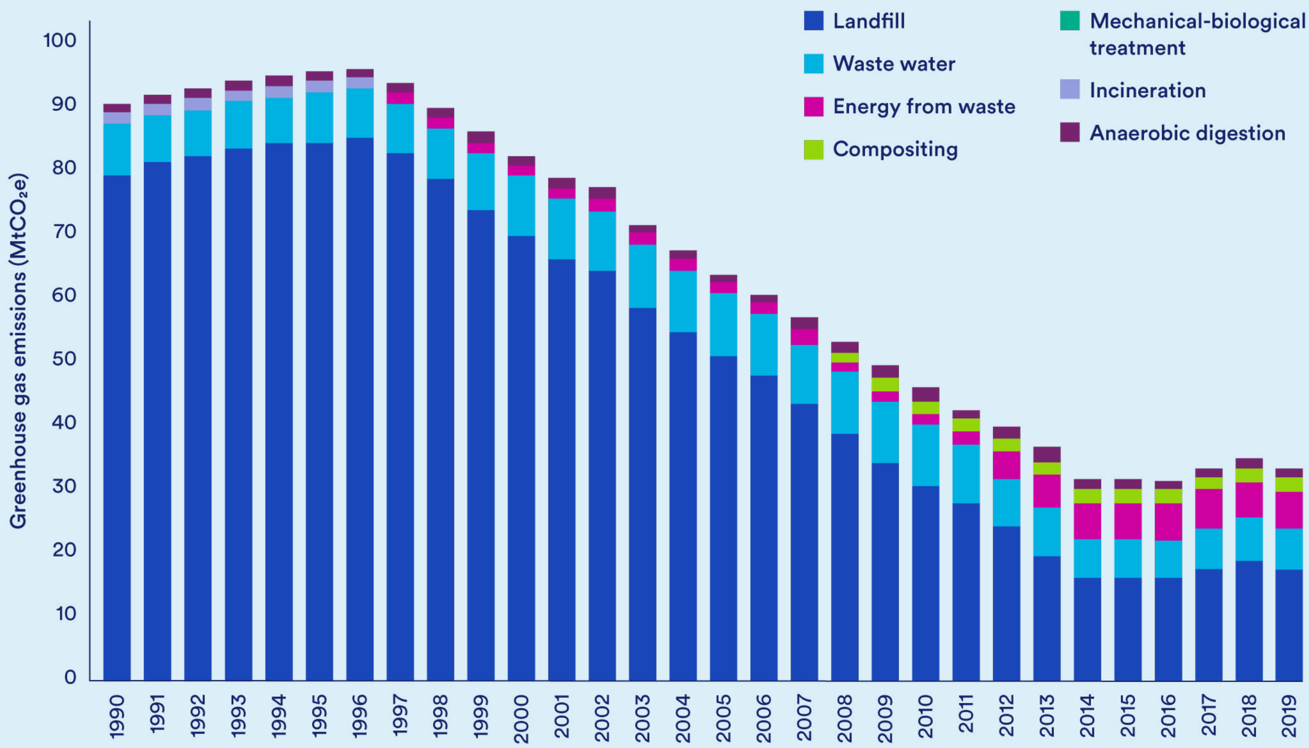
Elsewhere, the Klemetsrud plant in Oslo is a likely first feeder into Northern Lights, while waste to energy plants also make up a significant part of other Norwegian clusters like Borg CO_2 – a collection of emitters around the towns of Frederikstad and Sarpsborg.[69,70] In the UK, waste-to-energy plants account for nine of the 23 industrial capture projects deemed eligible or funding within the two prioritised clusters. In the Netherlands, AVR supplies local greenhouses with around 60 kt/year of CO_2 captured from its waste-to-energy plant in Duiven.[71]

The EU has signalled a desire to move away from waste incineration, excluding the practice from eligibility for European investment bank support or funding mechanisms such as the Recovery and Resilience Facility or Just Transition Mechanism.[72] While it is vital to continue the current trend of increasing recycle rates, for non-recyclable waste, incineration with carbon capture presents a promising alternative to landfill, which produces methane – a powerful greenhouse gas (**Figure 11**). Providing appropriately balanced incentives to promote recycling and encourage investment in cleaner, low-carbon incinerators – all while avoiding 'carbon leakage' from waste export to cheaper, more greenhouse gas-intensive operators – is highly challenging. In most countries, waste-to-energy plants are not subject to the EU ETS for their fossil CO_2 emissions, however, facilities in Denmark and Sweden are covered by the scheme, providing an additional incentive to reduce emissions. In Norway, a €14/t tax on fossil CO_2 from waste incinerators has recently been proposed, with the aim of increasing recycling rates.[73] In the UK, the sector has recently been declared eligible to apply for industrial carbon capture contracts, provided facilities meet a high efficiency standard.[59] For the Nordic countries, there is potential for deriving value from the growing market for carbon removal credits associated with biogenic waste, however, recipients of the UK industrial contracts will not be able to also apply for removal-based credits.

In an increasingly privatised and internationally competitive sector, there is a need to avoid incinerators with carbon capture installed being placed at a competitive disadvantage relative to unabated facilities. Some have proposed an export tax on waste to address this issue.

The small size of waste to energy facilities and their typical location within urban areas can also present a challenge for CO_2 transport. Several of the proposed sites envisage road-based transport of liquefied CO_2 to nearby ports. While a flexible and less capital-intensive option than pipelines, this solution brings its own challenges of large onsite storage, heavy road use, and the need for low-carbon road tankers.

Figure 11: A breakdown of waste sector emissions in the UK, showing the trend away from landfill (Viridor, 2021)[74]



Germany

Early efforts to deploy large-scale carbon capture on Germany's coal power plants met with failure, sometimes following strong local opposition to CO_2 storage, although a research-scale project at Ketzin successfully stored small amounts of CO_2 from 2008 to 2013.[75] Ultimately, these experiences led to a very limited implementation of the EU's CCS Directive in 2012, and German CO_2 storage law does not allow for the provision of new storage licences. However, in 2019, then Chancellor Angela Merkel put the technology back on the agenda, identifying it as a potentially crucial element in the country's decarbonisation plans.[76]

In December 2021, a new governing coalition released an agreement which includes several key priorities for energy and climate policy.[77] Although carbon capture and storage is not mentioned explicitly, the need for alternative, rapidly scalable forms of low-carbon hydrogen is highlighted. The agreement also sets out an intention to develop a long-term strategy for the technological removal of CO_2, aimed at dealing with the approximately 5% of emissions considered 'unavoidable' (63 Mt). More recently, the government has announced a CCfD-based support scheme for industrial decarbonisation projects, including facilities for the capture, use and storage of CO_2.

At a regional level, the heavily industrialised region of North-Rhine Westphalia has produced a carbon management strategy which envisages capturing up to 7 Mt of CO_2 per year from industries including cement, lime, steel, and chemicals.[78] This CO_2 could be transported either to proposed CO_2 shipping terminals at Bremerhaven and Wilhelmshaven, or to Rotterdam via the Delta Corridor – a cross-border CO_2 and hydrogen pipeline initiative led by the Port of Rotterdam and Rotterdam Rijn Pijpleiding. Within Germany, gas network operator Open Grid Europe has set out plans for the construction of a 964 km-long pipeline network, capable of transporting 18.8 Mt of CO_2 annually.

Other countries

The promise of open access storage infrastructure in the North Sea, typified by Northern Lights and Porthos, has proved highly effective in spurring industrial clusters and individual emitters in other countries around the North Sea and Baltic Sea to develop capture plans. Projects in Sweden which have been linked to Northern Lights include Stockholm Exergi's biomass heat and power plant and Preem's oil refineries in Gothenburg, while another major capture facility is planned for Heidelberg Cementa's Slite plant in Gotland. In Belgium, the Antwerp@C project has brought the port authority together with seven emitting industries in the area with the aim of developing shared CO_2 infrastructure.[79] As Belgium has no suitable storage geology of its own, related CO_2 capture plans such as Kairos@C are investigating pipeline or ship transportation to Rotterdam (for connection to the Porthos or Aramis storage sites) or Northern Lights. In France, the '3D' project in Dunkirk was formed by a consortium of 11 stakeholders, focusing on demonstrating the innovative DMX capture process on ArcelorMittal's steelworks by 2025, but with the ultimate aim of developing an industrial cluster in the port region.[80] This cluster aims to grow to 10 Mt CO_2 per year by 2025. Another potential capture cluster in Northern France is based around the Normandy industrial basin, where four emitters signed a memorandum of understanding (MoU) to develop CO_2 infrastructure and capture 3 Mt per year by 2030.[81]

Moving beyond the North Sea, some early-stage plans for carbon capture and storage projects can also be found in Southern Europe. In Italy, Eni's Ravenna Hub plans to capture 3 Mt CO_2 per year largely from Eni's own facilities across North-Eastern Italy, for storage in offshore depleted gas fields known as the 'Blue Adriatic' store.[82] In South-Western France, the Pycasso project is notable for featuring onshore storage in depleted gas fields, previously used to store 50 kt CO_2 as part of Total's successful Lacq-Rousse pilot project, which ran from 2010 to 2013 (*see case study*).[18] Pycasso would group together emitting industries from across South-Western France and Northern-Eastern Spain to feed into this geological basin.

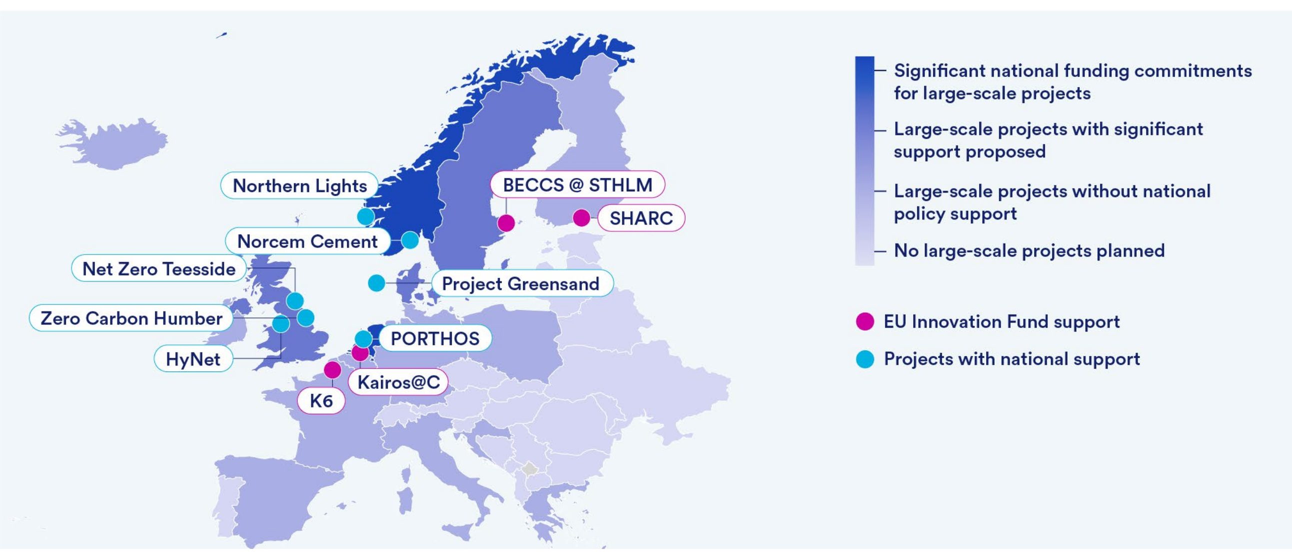
As noted, seven countries have included plans related to carbon capture and storage development in their applications to the EU's Recovery and Resilience package funding: Finland, Belgium, Denmark, Sweden, Germany, Croatia, and Greece.[38] The projects targeting this funding range from planned capture facilities, such as the Sisak ethanol refinery in Croatia, to pipeline infrastructure, such as Belgium's 'H_2 and CO_2 backbone', as well as more general packages to support industrial decarbonisation.

However, none of these countries has yet put in place national-level funding mechanisms or deployment targets for large-scale CCS projects, with most initiatives relying on applications to the EU's Innovation Fund and Connecting Europe Facility, or research and development funding through the Horizon Europe programme.

Table 4: A summary of national-level policies relevant to carbon capture and storage (CCS) deployment

Country	Capital support available to CCS projects	Operating support available to CCS projects	CO_2 transport and storage regulation	Ratification of amendment to London Protocol	Targeted support for CO_2 removal	Inclusion of CCS in NECP	Deployment targets or strategies
Denmark	€37 m to storage projects	€2.1 bn CCS funding pool for 0.9 Mt/year capture,	To be defined	Intends to ratify	€2.1 bn funding pool includes bio-energy combustion – separate pool for biochar, biogas, DAC	Yes (R&D)	0.9 Mt/ year by 2030 (combustion-based capture)
Germany	Industrial decarbonisation funding based on CCfDs	Industrial decarbonisation funding based on CCfDs	Currently forbidden	No	No (technical carbon removals in coalition agreement)	Yes (R&D)	No
Netherlands	SDE++	SDE++	Benchmark transport and storage tariff included in SDE++ subsidy	Yes	No	Yes	Cap of 9.7 Mt/ year (industry) and 3 Mt/year (power) for CCS subsidies under SDE++
Norway	€1.6 billion funding for 'Longship', some project-specific funding from Enova	Government funding includes majority of Longship operating costs	Commercially operated by state-owned enterprise	Yes	No	N/A	
Sweden	Included in €3.35 bn for bio-energy CCS scheme (2026-2046)	Included in €3.35 bn for bio-energy CCS scheme (2026-2046)	No storage sites planned	No	Reverse auction for bio-energy CCS (2022)	Yes	No
United Kingdom	£1 billion to T&S infrastructure and industrial carbon capture, also capital repayment component in capture plant business models	Contracts for difference for power (Dispatchable Power Agreement), Industry (ICC), and low-carbon hydrogen	Transport and storage to be operated on a regulated asset base model – fixed rate of return	Yes	Under consultation – likely DPA + top-up payment for Bio-energy CCS power, 5 Gt target	N/A	20-30 Mt/year CO2 captured and stored by 2030

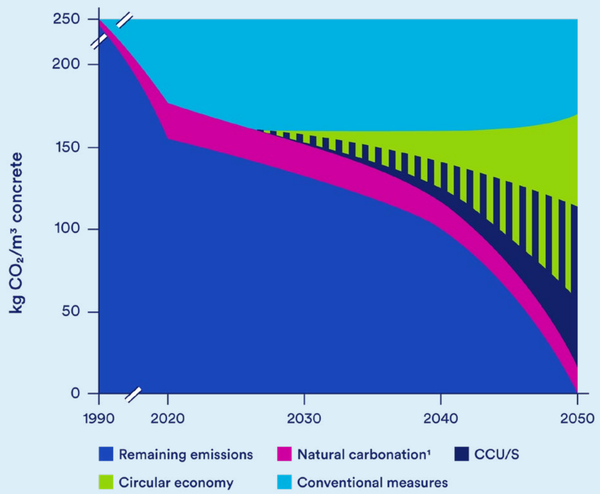
Figure 12: The funding policy landscape for carbon capture and storage in Europe, showing notable funded projects



Sector case study: Cement

The cement industry, together with the closely related production of lime, is the most greenhouse gas intensive industry in Europe, accounting for nearly 190 Mt of CO_2, or around 5% of the region's CO_2 emissions.[13] As the key 'binding' ingredient in concrete, cement production is closely linked to global growth, and has more than doubled in the last two decades. Around two thirds of the CO_2 released by cement and lime plants are a result of the inescapable chemistry of the process: the calcination of calcium carbonate to calcium oxide. The remaining emissions come from the various fuels used to generate the heat which drives this reaction. While the fuel's carbon emissions could potentially be avoided through the use of lower-carbon fuels such as climate-beneficial biomass or hydrogen, there is currently no other option for dealing with cement 'process emissions' other than carbon capture. Consequently, the cement industry is at the forefront of many of the early plans for carbon capture and storage around the world and in Europe.

Figure 13: HeidelbergCement's pathways for reducing cement emissions[85]



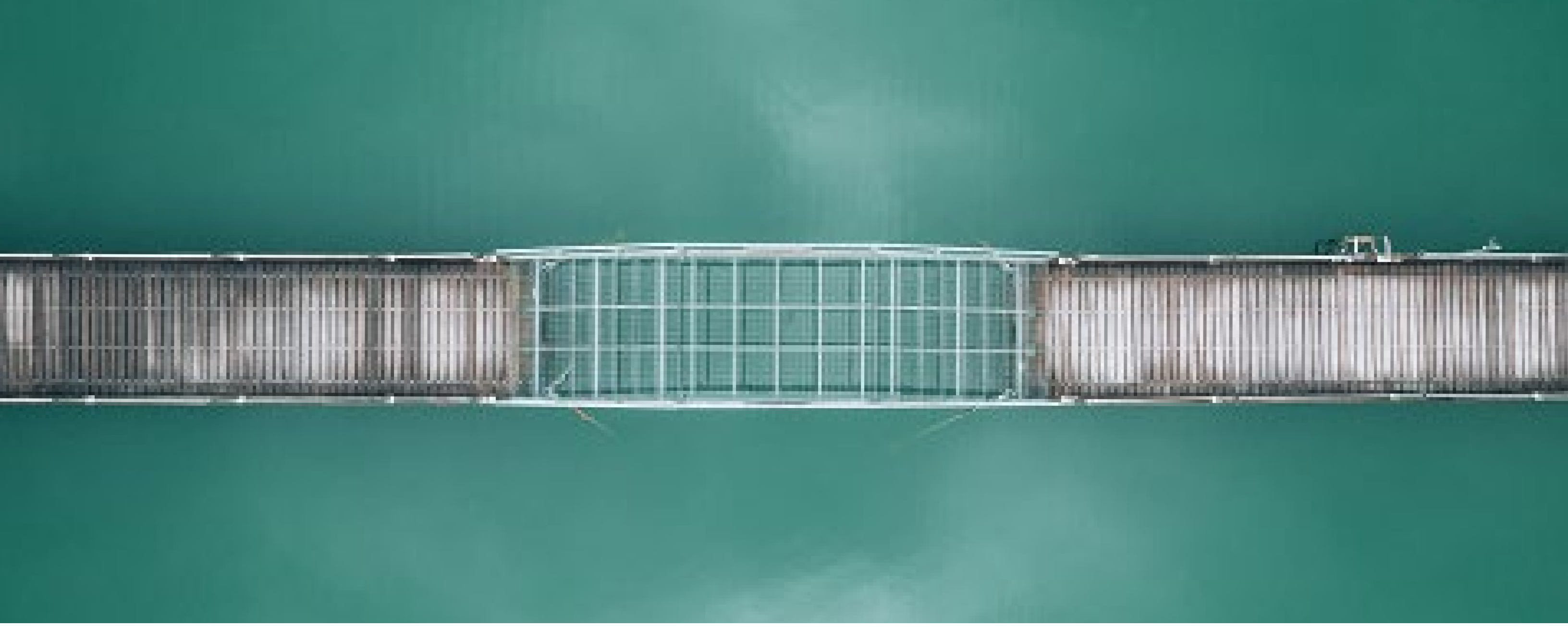
1) Natural carbonation is the absorption of CO2 from the atmosphere during the lifetime of a concrete construction

The most advanced of these plans, Norcem's Brevik plant in Norway has been selected as the first source of emissions for the Northern Lights storage project and is scheduled to start in 2024. Norcem is a subsidiary of HeidelbergCement, which has a number of other initiatives throughout Europe, usually also through local subsidiaries. In Sweden, Cementa's Slite plant on the island of Gotland is a proposed project currently undertaking a pre-feasibility study for the capture of 1.8 Mt per year by 2030.[83] In the UK, the Hanson cement plant in North Wales aims to be one of the first industrial sites to supply CO_2 to the HyNet cluster, launching a carbon capture feasibility study in 2021. Eqiom's cement plant in Northern France has been selected by the EU's Innovation Fund to install a form of carbon capture known as oxyfuel – this will likely deliver CO_2 for export from a terminal at Dunkirk. Carbon capture also features heavily in the decarbonisation plans of French-Swiss cement giant LafargeHolcim, which is involved in around 20 projects globally, including the Pycasso cluster in France and Spain.

These cement producers and many others have signed up to the 'Business Ambition for 1.5°C Commitment', an initiative led by the Science Based Targets Initiative, which requires corporate decarbonisation actions to be consistent with net zero in 2050. In 2021, the Global Cement and Concrete Association (representing over 80% of cement production outside of China) published a roadmap for realising net zero concrete, estimating carbon capture would contribute 36% of total CO_2 reductions globally (1370 Mt).[84]

The options available for decarbonising concrete are further laid out in **Figure 13**, which shows HeidelbergCement's vision for a zero-carbon material.[85] A significant portion of CO_2 emissions can be eliminated through 'conventional measures', which refers to the use of more efficient plants, alternative fuels, and increasing the proportion of alternative feedstocks such as industrial wastes. To some extent, CO_2 is recaptured by the concrete itself as the calcined minerals in the product slowly react with CO_2 in the air. The recycling of used concrete could also play a big part in diminishing the total carbon intensity of the final product. The relative size of the roles of this 'circular economy' approach and carbon capture are left uncertain – depending to some extent on future build rates – but there is little doubt that the industry will need carbon capture to remain viable in a net-zero world.

A challenge for the cement and lime sector is the typically remote locations of plants, which are generally located close to quarries and local customers, rather than as part of the heavy industry 'clusters' which form the focus of many CO_2 infrastructure projects. For coastal sites like the Brevik plant, shipping provides a solution, but inland plants without ready access to storage may need to initially rely on non-pipeline transport modalities such as road tankers, rail, or river barges. This will require liquefaction and CO_2 storage capabilities at the plant site.



SECTION 4

Closing the funding gap

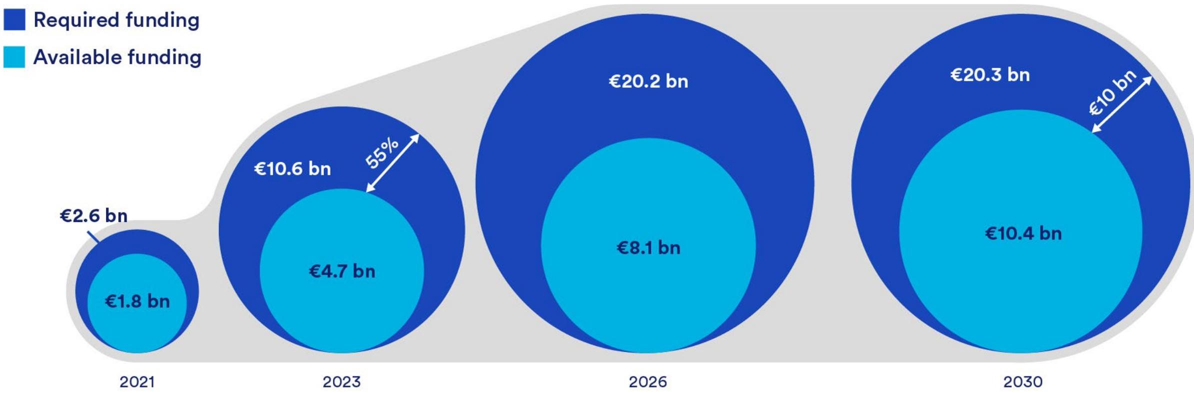
Analysis of the policy landscape for carbon capture and storage around Europe highlights that the most immediate barrier to the technology is a shortage of funding for many early-mover projects. While the Innovation Fund represents a welcome and much-needed source of capital and operational cost support to projects, it is heavily over-subscribed, with more than 300 applicants to the first call reduced to seven successful candidates. Particularly in these early stages of deployment, where shared CO_2 infrastructure is still to be put in place, much more significant levels of funding are required. The Innovation Fund is also limited to demonstration of new technologies, preventing it from supporting the first few generations of carbon capture plant which are so essential for derisking technologies for commercial investors.

Most early projects which appear to be moving towards positive final investment decisions are therefore heavily reliant on spending commitments by national governments, often providing both a portion of the initial capital investment and closing the gap between project operating costs and the carbon price.

Analysis by Carbon Limits for CATF highlights the extent of this funding gap, by comparing the net present value of projects proposed today with the estimated funds available from existing national and EU support packages.[84] Figure 14 shows the cumulative net present value shortfall of all projects scheduled to require financing by a given year (taken as three years prior to their targeted start date), assuming a carbon price which increases to €93/t in 2030 and a generic cost for transport and storage. By 2030, the unrecoverable investments made by all planned projects amount to over €10 billion. For these projects to represent profitable and therefore financeable initiatives, this shortfall must be met by some form of additional funding – ideally in the form of ongoing operational support with a high level of future certainty. However, the estimated funds available from existing support schemes cover less than half the shortfall throughout most of the analysed period.

Funding the initial roll out of carbon capture and storage, from first of a kind to ‘nth of a kind’ plants, is a complex policy challenge requiring different incentives for different parts of the process chain. Establishing early transport and storage infrastructure can be a highly capital-intensive endeavour with long development times and problematic risks associated with the potential for stranded assets. As a result, several of the first-mover infrastructure projects, such as Porthos, Northern Lights and the UK clusters, depend on significant capital grants from their host governments, particularly for high-risk early phases prior to a final investment decision.

Figure 14: The gap between announced funding for carbon capture and storage and the funding announced projects require to have a positive net present value (cumulative over time)[86]



In the short-term, direct capital grants or government-backed loans for infrastructure are likely to remain essential if adequate storage volumes are to be developed in rapid timeframes. However, to enable emitting industries to make use of this new infrastructure in their decarbonisation strategies, policy also needs to reward the capture of CO_2 through sustained, stable revenue streams with a degree of long-term certainty (at least ten years). Such incentives provide a stronger and less volatile carbon price signal than the market price, allowing new projects to build and operate CO_2 capture equipment and support the payment of a regulated tariff for CO_2 offtake. In these early stages of development for a nascent carbon management industry, bankable revenue streams are essential for attracting a broader base of project finance, including large-scale, more risk-averse lenders, thus lowering the cost of finance and overall project costs. Beyond the value of the funding itself, strong government support also signals a political commitment to carbon capture as a decarbonisation tool, building industry and investor confidence.

To date, the Netherlands is unique in Europe in having implemented a subsidy framework covering both the capital and ongoing operating costs for carbon capture and storage projects, in the form of the SDE++ scheme. A similar model seems likely to be adopted in the UK, where Industrial Carbon Capture Contracts would take the format of a contract for difference, effectively guaranteeing an elevated carbon price to the emitter. These schemes, along with the recently proposed Danish fund, are notable as the only dedicated revenue models for large-scale carbon capture in Europe. In Norway, the state has agreed to cover additional operating costs for the Brevik cement plant required to kickstart the Northern Lights storage facility – however, for follow-on capture projects and other clusters, a more repeatable and competitive support framework will be necessary.

These examples indicate that adequate long-term revenue certainty for CO_2 capture projects – particularly beyond first-of-a-kind plants – is likely to primarily depend on national policy, rather than centrally allocated EU initiatives. The form which this business model takes will therefore inevitably vary between jurisdictions, at least in the medium term. National governments have tended to develop incentives which build on or imitate existing support schemes for renewable energy; this adaptation of well-established instruments can help rapidly gain confidence from developers and the financial community.

Recommendations:

- Increase the size of the Innovation Fund and consider frontloading funding to earlier in the decade to promote earlier project development – particularly for critical infrastructure which can enable follow-on projects to bid at lower cost
- At the EU and national level, implement forms of operational subsidy for CO_2 capture plants (such as carbon contracts for difference) that can provide bankable revenue streams to early projects
- Ensure new and existing subsidy schemes for industrial decarbonisation are accessible to carbon capture and storage projects
- Ensure capture rate requirements are imposed on a 'process stream' level, rather than a whole plant level

SECTION 5

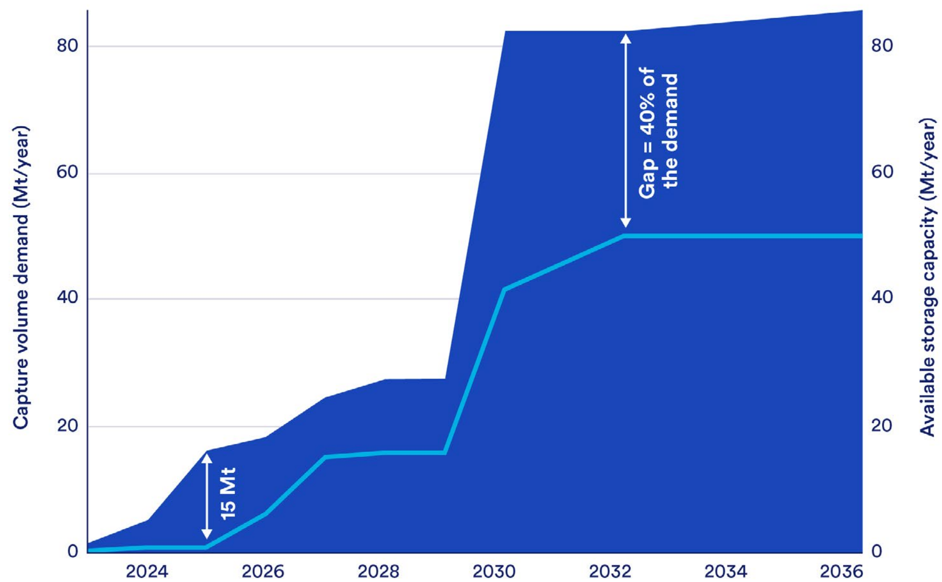
Establishing large-scale, open-access storage

Developing shared infrastructure for the transport and storage of CO_2 is the central challenge of the current phase of carbon capture and storage deployment. Unlike some low-carbon technologies – notably wind and solar power – CO_2 storage capacity cannot easily be incrementally built up in a modular fashion, but requires significant upfront investment in facilities with the capability to store at least tens of megatonnes of CO_2. Although additional pipeline networks and CO_2 injection sites can be expanded in a phased manner over time, even initial transport infrastructure typically requires capacities of at least 1 Mt CO_2 per year to achieve reasonable economies of scale.

Analysis for CATF by Carbon Limits shows that the demand from currently proposed CO_2 capture projects far outstrips the capacity available from storage sites currently under development (**Figure 14**).[87] This shortfall becomes particularly marked after 2030, which is the target date for many first-mover clusters to expand or for projects currently at an early stage of development to be commissioned. As much as 40% of demand may go unmet if further storage sites are not developed during the 2020s, and this gap is likely to widen as more industrial sites put forward decarbonisation plans (**Figure 15**). Given that storage sites typically have long project lead times, covering extensive site characterisation and permitting requirements, it is a matter of urgency to ensure that new initiatives are begun early in the decade.

The reuse of existing infrastructure can play an important role in enabling fast-moving projects which can quickly expand; in particular, existing gas pipelines which are nearing or have reached the end of their use for gas extraction can potentially be repurposed for CO_2 flow in the other direction. This approach, along with the reuse of offshore platforms associated with already well-characterised geology and depleted gas fields, can significantly reduce project development times and capital costs. It forms the basis of several UK proposals including the HyNet, Acorn, and V Net Zero projects, and reuse of existing gas pipelines is under consideration by the Pycasso project in France. Government policy can play a role in encouraging the reuse of existing infrastructure by identifying key assets and regulating industry to ensure these assets are maintained if they are likely to require repurposing for CO_2.

Figure 15: The widening gap between volumes of CO_2 captured and available storage, based on current project announcements[87]



There is also a clear role for government in supporting the geological characterisation work required to accelerate the development of new storage sites, particularly with respect to saline aquifer resources. In the USA, the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative is a Department of Energy-funded programme which fully develops large-scale (at least 50 Mt capacity) storage sites at key locations around the country, bringing them to a point where they are fully characterised, permitted for CO_2 injection, and available for commercial use.[88] A similar model could usefully be adopted in the EU, where there is a need to go beyond basic geological appraisals and mapping to establishing 'ready-to-use' storage assets across the region.

Ultimately, the need for shared CO_2 infrastructure presents a fundamental question over the respective future roles of the public and private sector. Early projects such as Porthos and Northern Lights have been reliant on a high degree of public sector involvement, including the participation of state-owned enterprises, large capital grants, and government bearing many project risks. Individual countries have varying visions of the extent of public involvement required in a future carbon management industry, and first-mover countries are charting their own courses. A more regulated industry with limited returns for developers (as proposed in the UK) can lower costs for early capture projects, when storage operators may have effective monopolies, but may limit expansion. On the other hand, a more competitive market for CO_2 storage services could increase the risk appetite of the sector and accelerate expansion plans. In the long-term, there is likely to be a role for the EU in ensuring a level playing field between CO_2 storage operators, avoiding monopolies, and fostering a competitive environment for storage in which smaller or specialist developers can enter the market.

Recommendations:

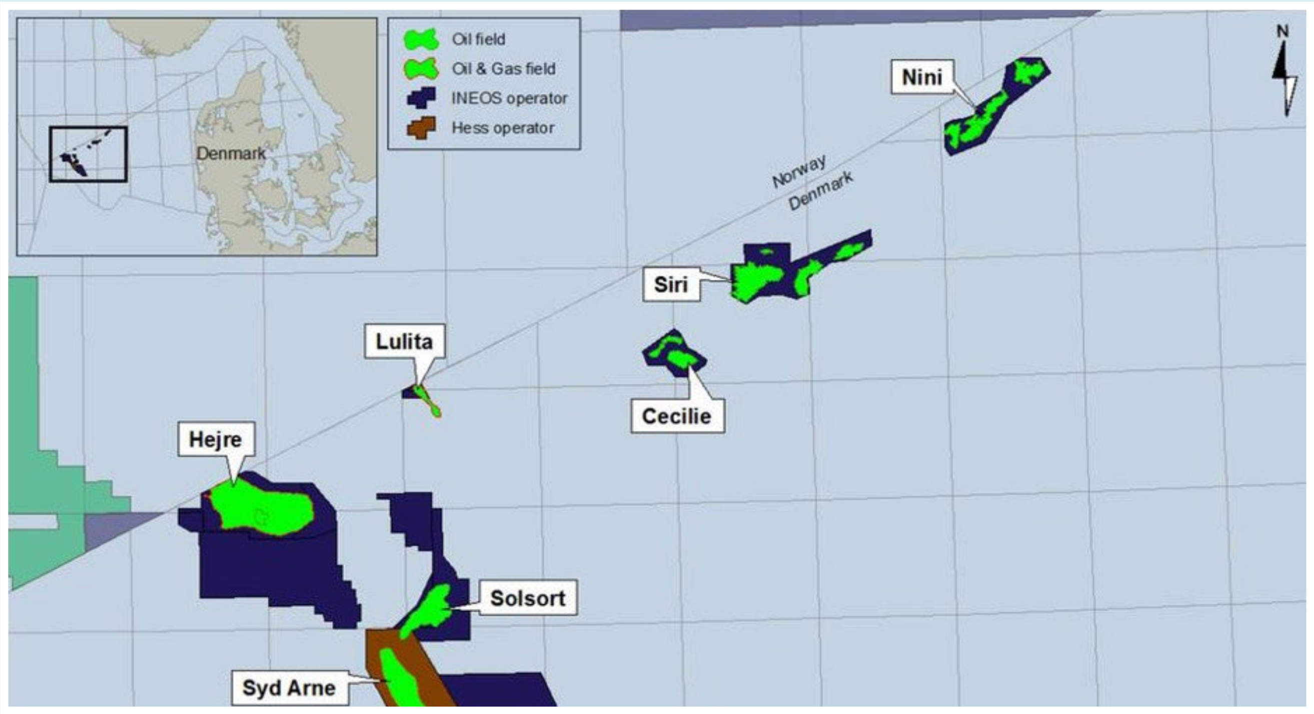
- Support for early, large-stage characterisation and development of large-scale stores (100 Mt+) on a coordinated, cross-border basis (such as direct grants, loans, tax credits)
- Introduce regulatory requirements for the oil and gas industry to undertake steps towards CO_2 storage, including exploration, data acquisition and sharing, and permitting
- Create new financial instruments to cover the small, but challenging risk of CO_2 leakage, such as mandatory insurance funds
- Incentivise industry to reuse existing infrastructure for CO_2, potentially through public support for maintenance, purchase of key trunklines, or regulatory obligations to consider reuse before decommissioning
- Provide a standardised set of EU recommendations for streamlining storage site permitting
- Steer towards a robust regulatory framework for the CO_2 storage industry, ensuring third-party access and clarifying risk allocation across the process chain

Storage project case study: Greensand

Launched in June 2020, soon after Denmark's new political commitment to carbon capture and storage, Project Greensand is an initiative to develop CO_2 storage in the Danish North Sea, led by INEOS Energy with a consortium of 22 partners).[89] The first phase of the project, covering technical validation of the Nini West Field (a depleted oil reservoir) was supported by funds from the Energy Technology and Demonstration Program (EUDP) and completed in 2021. In this phase, the project assessed how the reservoir will respond to CO_2, as well as establishing the basis of the well design and assessing how much of INEOS's existing offshore infrastructure can be repurposed. In August 2021, the project moved to a second phase which will include a three-month test injection of around 12,000 tonnes of CO_2 starting from late 2022, using containers of liquid CO_2 delivered by ship from the Port of Antwerp.[90] In contrast to Northern Lights, which uses an onshore collection terminal, Greensand plans to deliver CO_2 directly to the injection platform by ship. Further government funding of DKK 197 (€26 million) will cover around 40% of the costs for this second phase of the project.

Preparatory work for full-scale injection of up to 1.5 Mt of CO_2 per year in the Nini reservoir also began in 2022 (including the development of dedicated CO_2 carrier ships), with a view to proceeding to an operational phase in 2025. The potential to expand to nearby depleted reservoirs and underlying saline aquifers could bring the total storage capacity to 4-8 Mt per year by 2030 (**Figure 16**); the upper estimate would be equivalent to a quarter of Denmark's total emissions.[91] However, sourcing dependable volumes of captured CO_2 in Denmark or nearby countries is a key prerequisite for investment in the full-scale project and the expansion phase.

Figure 16: The location of the Greensand storage site at Nini West and surrounding oil and gas fields considered for the expansion phase[91]



SECTION 6

Building beyond the North Sea

Carbon capture and storage has the potential to be an equitable climate solution for the whole of Europe – not just the countries around the North Sea which are the focus of most activity today. There is suitable geology for safe CO_2 storage in nearly every Member State, with particularly promising resources in Romania, Poland, Croatia, and the Czech Republic. However, developing CO_2 storage capacity in Central and Eastern Europe faces challenges, including the need to improve regulatory frameworks and build relevant experience and expertise within government and local oil and gas companies that are likely to lead early projects. Unlike the North Sea initiatives, most of the storage in these regions will take place onshore, requiring careful engagement with local residents and other stakeholders.

To date, three successful trials of onshore CO_2 storage have taken place in Europe: at Lacq-Rousse in Southern France, Ketzin in Brandenburg, Germany, and Hontomin in Northern Spain, all of which enjoyed good relationships with local communities through close engagement. More recently, a few research projects have sought to lay the groundwork for further CO_2 storage pilots in Southern, Central and Eastern Europe, including the EU-funded research projects 'Strategy CCUS' and 'Enabling onshore CO_2 storage (ENOS)' and 'CCS4CEE', funded by EEA and Norway Grants.[92,93,94] These initiatives have identified promising sites, raised awareness and identified actions for further development, but a move to actual trial injections of CO_2 is required if these regions are to also have timely access to storage sites which can allow their industries to decarbonise.

For many countries, there remain serious gaps in the implementation of the EU's CO_2 storage directive, which can effectively prevent any form of storage. This issue becomes particularly problematic for countries wishing to store CO_2 close to a border with a neighbour which has banned the practice, given the possibility of subsurface migration across the boundary. In this respect, the EU can play a coordinating role in helping those Member States that wish to store CO_2 to bring their regulations into line with states with more established protocols, and to develop guidelines for resolving cross-border issues.

The EU supports several funding mechanisms to assist with the costs of transitioning to a greener economy; in particular, the Just Transition Fund is aimed at supporting parts of Europe which are currently heavily dependent on coal and other fossil fuels. Under certain conditions, it can be used to support investments in emissions reductions from industry, including the use of hydrogen. However, it is important to recognise that developing CO_2 storage sites, particularly in Central and Eastern Europe, will have an important role to play in enabling the long-term viability of job and livelihoods associated with vital local industries, and that storage sites may not always be located within the regions which depend on their development.

Recommendations:

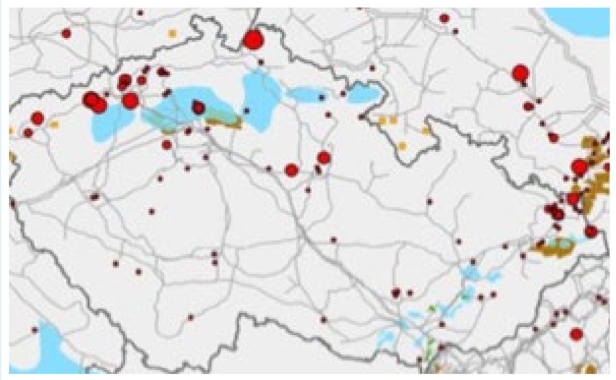
- Promote capacity building initiatives for government and other stakeholders in key Member States
- EU-coordinated efforts to update carbon storage regulations in Member States
- Identify promising, large-scale onshore or offshore storage regions in Southern, Central, and Eastern Europe and ensure they are developed to the point where they are 'injection ready'
- Explore ways in which the Just Transition Fund could be used more broadly to help decarbonising regions to access CO_2 storage

Country case study: Czech Republic

The Czech Republic is a heavily industrialised country in Central Europe which is likely to need carbon capture and storage to meet the EU's net zero target. Of roughly 110 Mt of CO_2 emissions in 2018, around 50 Mt was associated with the energy industry (mostly from lignite coal for power generation) and 16 Mt from industrial processes such as steel, refineries, and cement.[95] The country also has good geological potential for storing CO_2, with a total capacity estimated at between 850 Mt and 3 Gt, largely along the Northern and South-Eastern borders and close to most large emitting sources (**Figure 17**). Previous efforts to develop carbon capture have included several EU-funded research projects on capture technologies, mapping possible transport networks, and assessing suitable storage sites. Although no large-scale capture or storage demonstration has yet been realised, an ongoing project known as CO_2-SPICER aims to lay the groundwork for the first ever trial storage of CO_2, using a depleted oil field in the Vienna Basin close to the border with Austria and Slovakia. Scheduled to conclude in 2024, this project could potentially be followed by a construction phase. Heidelberg Cement is also interested in implementing carbon capture and storage at the plant of its Czech subsidiary Ceskomoravský Cement – this would involve CO_2 storage in a depleted oil field. These plans require the close participation of oil and gas company MND, which is increasingly active in supporting carbon capture projects and policy development in the country.

However, commercial storage of CO_2 was prohibited in the country until the expiry of a long-standing ban in 2020. Although CO_2 storage is now theoretically possible, in practice, it requires a more thorough transposition of the EU's CCS Directive into Czech law through a new Implementing Decree; work on this is currently underway by the Ministry of Environment. In particular, the Decree needs to address the financial guarantees required of companies storing CO_2, which would cover future costs of monitoring and verifying the storage site for eventual transfer to the state. As the technology progresses, there is also a need for greater human resources and capacity building on carbon capture and storage within government.

Figure 17: Emission sources (red) and potential CO_2 storage areas (blue) in the Czech Republic[95]



SECTION 7

Coordinating clusters and common infrastructure

The conceptual separation of CO_2 capture projects from storage infrastructure has helped drive much of the recent development in Europe, by freeing emitters from the costs, risks, and complexities of infrastructure planning. There is growing consensus that this model, in which CO_2 transport and storage is provided as a third-party service to emitting industries, will be the future of the industry. However, during these earliest stages of development, this approach brings coordination challenges as well as flexibility, many of which are shared by other infrastructure-reliant climate solutions, such as hydrogen networks and electric vehicles. Often known as the 'chicken and egg' problem, developers are reluctant to invest in large infrastructure without some certainty that it will be filled with captured CO_2, while emitters will not invest in CO_2 capture without certainty that they will have access to an 'off-taker' for the greenhouse gas. Mitigating this stranded asset risk has therefore become a central theme in carbon capture policy design and project development, usually through careful coordination between companies and a degree of state involvement and regulation.

In the examples set by Norway's Northern Lights project and Porthos in the Port of Rotterdam, it is clear that development of these ostensibly independent infrastructure projects have needed to progress in lockstep with the emitting industries which will ultimately provide their revenue. In both cases, the developers have worked with first-mover emitters in the region, initially signing agreements such as MoUs and ultimately relying on state subsidies to commit to supporting all elements of the process together. For Porthos, this required all four initial emitters to successfully obtain support through the first round of the SDE++ mechanism, thus providing the revenue stream which would allow them to pay for CO_2 offtake. For these early projects, final investment decisions will generally be taken for all elements of the chain together.

Through its phased cluster competition, the UK has explicitly acknowledged that carbon capture and storage is a collaborative endeavour within a region, while seeking to maximise value with a competitive element. This process has initially focused on prioritising industrial regions with accessible and relatively developed storage sites which can receive funds for infrastructure support. Similar to Northern Lights and Porthos, cluster bids required close collaboration between the 'cluster leads' – often an oil and gas company developing the storage site – and emitters in the area, ideally including some lower-cost, 'low-hanging fruit' emissions which could be quickly developed. While these emitters will still have to compete to win a package of revenue support from government, any early investment in the transport and storage infrastructure is reliant on a commitment from government to support enough emitters (with long-term viability) to fill the first pipeline.

Most of these early infrastructure projects aim to gradually expand in a phased manner, adding CO_2 injection sites and potentially new pipelines or ships over time, and this too will continue to require close collaboration with new emitters. Northern Lights has already embarked upon this process by establishing MoUs with numerous industrial sites around Northern Europe. However, with planned storage infrastructure generally oversubscribed and funding for capture plants limited, many emitters will have to stall capture plans until more storage or funding is made available.

These first-mover experiences highlight a clear role for careful policy design in minimising this prominent 'ecosystem challenge' for the development phase of carbon capture and storage technologies. Government funding towards storage and infrastructure development must be coordinated with support for emitters to install and operate capture plants. Additionally, support for emitters should consider not simply the lowest cost CO_2 capture opportunities, but must take into account the added value and economies of scale in promoting clusters of co-located emitters, as well as opportunities for expansion. In Europe, such clusters have tended to develop organically through regional cooperation between industries, but the current policy frameworks are often poorly equipped to help these initiatives reach a collective final investment decision. Ultimately, these project risks will be expressed as higher project costs and create a larger or even prohibitive burden on state finances. Policy can also help develop strategies for reducing the risk posed by the withdrawal of one emitter, such as through the mandatory creation of mutual funds.

As carbon capture and storage moves past n^{th}-of-a-kind projects into an expansion phase, these coordination challenges will diminish. Transport and storage companies will have a broader portfolio of emitters from which to source CO_2, and some emitters may have a choice of established CO_2 offtake options, reducing the risk posed by a loss of a single project. Over time, the insurance sector will also become better placed to help developers mitigate these risks as they gain familiarity with the emerging sector.

Recommendations

- Enable national and EU funding support to look beyond a project-based assessment to exploit regional synergies and maximise economies of scale
- Consider regional scalability of carbon abatement potential as a key criteria in funding
- Develop risk management strategies and investable business models which can encourage the steady expansion of cluster networks

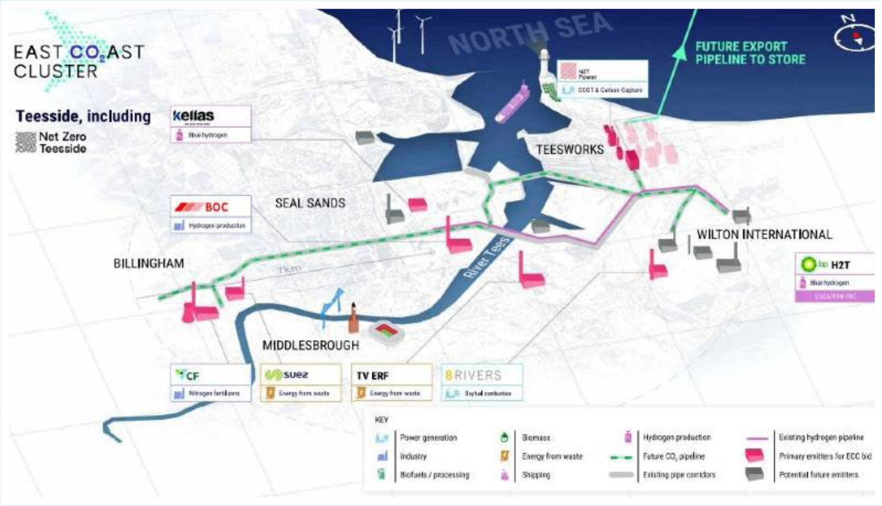
Cluster case study: The East Coast Cluster

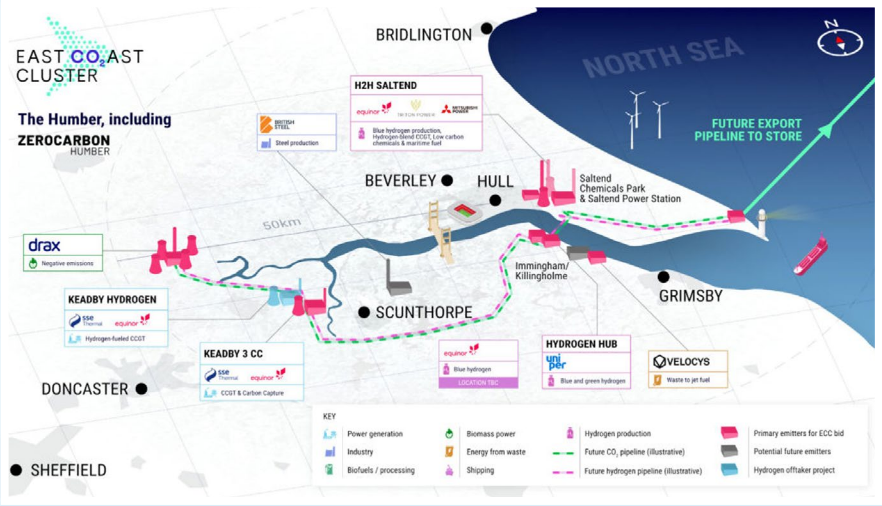
The north-eastern coast of England is home to a high proportion of the UK's heavy industry and power generation, mostly centred on the river estuaries known as Teesside and Humberside. Both these regions have featured prominently in earlier, aborted plans to develop carbon capture in the UK, but have evolved and joined forces to establish the East Coast Cluster (ECC), which successfully gained 'Track 1' prioritisation in the UK's cluster competition. This plan is centred on the 'Endurance' offshore storage site in the Southern North Sea, a saline aquifer which was originally characterised for earlier capture plans at Drax coal power plant. A consortium known as the Northern Endurance Partnership, consisting of BP, Eni, Equinor, NationalGrid, Shell, and Total, jointly owns and operate this site, which will serve both the 'Net Zero Teesside' cluster and the 'Zero Carbon Humber' clusters to form the ECC (**Figure 18**).[96]

Both regions include a wide range of existing CO2-emitting industries, including refineries, petrochemicals, fertiliser production, waste-to-energy plants, steel production, and gas and biomass-fired power plants. However, a significant portion of CO_2 emissions planned for the cluster are associated with new developments, including Equinor's H2HSaltend facility on Humberside which will produce blue hydrogen and chemicals, SSE Thermal's plans for a new gas-fired power plant at its existing Keadby site on the Humber, and BP's proposed 'Net Zero Teesside Power' project, which will also be based on a new combined cycle gas turbine. Other, smaller emitters included in initial plans for the clusters include oil refineries on the south bank of the Humber, CF Fertiliser's ammonia plant on Teesside, and Suez's energy from waste plant (Teesside). It remains to be decided which of these facilities will be prioritised as the first projects to connect to the infrastructure, with associated contracts for revenue support, but it is likely that at least one large emitter (either hydrogen or power production) will be required at each location. In total, 24 capture project proposals across the two regions have been identified as meeting the government's eligibility criteria for funding.[97]

Both Net Zero Teesside and Zero Carbon Humber require the build-out of significant CO_2 pipeline infrastructure to connect all the emitters to storage. An onshore pipeline in the Teesside area will extend over 10 km inland from the coast to Billingham, while a much longer pipeline on Humberside may ultimately need to extend up to 90 km to Drax biomass power plant. New offshore pipelines are required to link both locations to the offshore storage site, with the (more distant) Teesside location nearly 150 km from the site. The combined East Coast Cluster aspires to store up to 20 Mt CO_2 per year by 2030.

Figure 18: The proposed CO_2 infrastructure and potential capture plants in Net Zero Teesside and Zero Carbon Humber[96]





SECTION 8

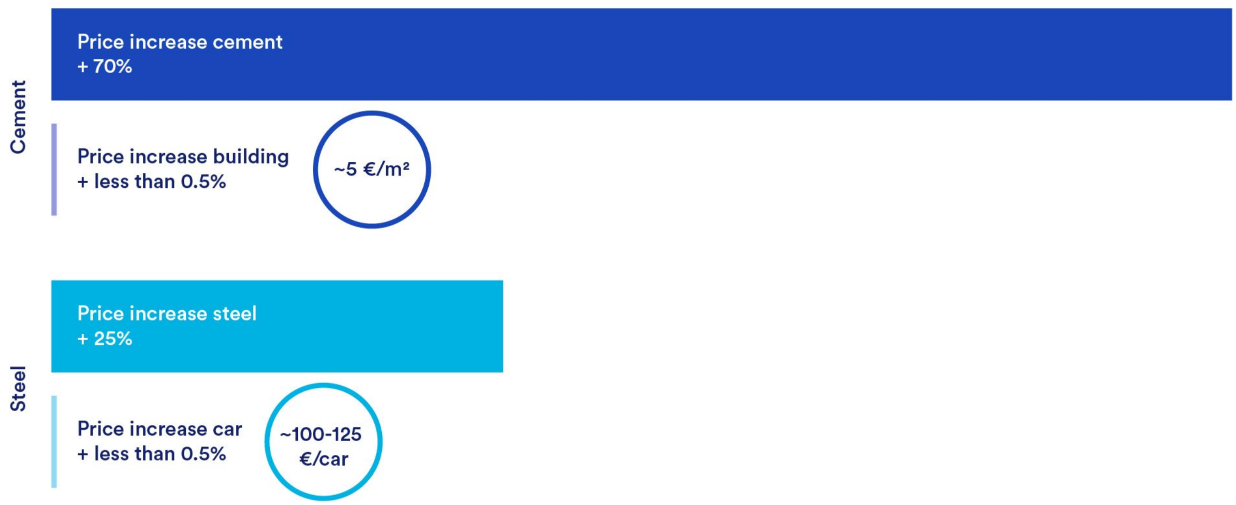
Moving to a market for low-carbon products and services

With adequate support for the first few projects in key sectors, carbon capture and storage should be able to move into an expansion phase in the early 2030s. At this stage, policy must aim to create more market-driven incentives for carbon capture which, in the case of manufacturing industries, will be centred on developing a market for low-carbon products such as steel, cement, plastics and chemicals. This shift will likely take place in the context of high carbon prices (>€100/t) and investors and developers will be in a position to take on many of the project costs and risks which are currently backed by governments.

Regulatory approaches for directly incentivising the manufacture of low-carbon products could include sales taxes based on embedded carbon or carbon intensity limits on certain products.[98] These levers can be applied at various parts of the value chain; the relative cost increase associated with decarbonised steel or cement will be much smaller – as little as a 1-2% increase – when considered against the total cost of 'end-use', consumer products such as a car or a house (**Figure 19**). For some high-value consumer goods, there are signs that voluntary demand and corporate net zero targets could initiate demand for decarbonised raw materials. Car manufacturers such as Volvo, Mercedes-Benz, and Volkswagen have all pledged to achieve carbon neutrality by 2050 or earlier, and Volvo have formed a partnership with Swedish steel producer SSAB to help develop green steel.[99,100] In 2021, ArcelorMittal launched its 'XCarb' scheme for certifying low-carbon steel throughout the supply chain.[101]

There is an important role for policy and regulatory actions to accompany these industry-led initiatives and kickstart developments in sectors with less scope for marketing premium products. Most significantly, governments must formalise and standardise certification for embedded carbon in products, based on robust life cycle analysis and potentially building on existing sustainability certification systems. In some sectors, such as construction, setting limits for embedded carbon in new buildings could establish a significant market for low-carbon cement and steel, with the option of making limits progressively more stringent. Governments can also help spur initial demand

Figure 19: The relative price impact of decarbonised cement and steel in end-use sectors[102,103]



by requiring the use of low-carbon products in public procurement of goods, buildings, or services, as well as raising public awareness of embedded carbon.

In the EU, these measures would likely be implemented through the Sustainable Products Initiative expected in 2022, which aims to establish market incentives for products with reduced climate and environmental impact, including cement, steel, and chemicals.[104] International precedents include California's 'Buy Clean California Act' (2017), which introduces a maximum acceptable emissions intensity for steel, glass, and insulation and requires suppliers to State projects to submit life-cycle assessments.[105] While these legislative measures will not initially set levels commensurate with carbon capture, through close coordination with industrial decarbonisation policy, they should be tightened over time to reflect the growing availability of the technology.

Market demand may drive carbon capture deployment in service industries as well as products. For example, decarbonised waste-to-energy plants could enable municipalities to contract for low-carbon waste disposal, helping them achieve local net zero targets while creating a competitive market based on carbon intensity as well as cost.

The development of demand-driven value in low-carbon products is closely linked to the forthcoming implementation of a carbon border adjustment mechanism (CBAM) for the EU ETS region. Scheduled to take effect from 2026, this proposed EU initiative intends to impose a levy on non-EU imports of electricity, cement, aluminium, fertiliser, and iron and steel products, based on their carbon intensity and the EU ETS price.[106] This aims to level the playing field between domestic producers, which have to pay for emissions, and imports from regions with less stringent (or absent) carbon pricing regimes. In general, the CBAM represents a positive move towards a more competitive, market-led model, where carbon-intensive industries are more exposed to the carbon price rather than receiving free emissions allowances. However, it must be carefully implemented if it is to truly incentivise EU industries to decarbonise, with parallel support for enabling infrastructure for hydrogen supply and carbon management. As it requires the implementation of a complex process for the verification and calculation of embedded carbon, the CBAM could also be used to support low-carbon product certification and raise consumer awareness of product carbon footprints within the EU.

Recommendations

- Develop rigorous low-carbon product certification, including effective tracking of carbon footprints through the value chain
- Implement public procurement of low-carbon raw materials such as concrete, steel, and chemicals
- Introduce carbon intensity limits for key end-use sectors, such as construction, that tighten in accordance with technology development
- Set targets for the increased adoption of low-carbon products on a sectoral basis

SECTION 9

Driving permanent carbon dioxide removals

Since the IPCC's 2018 assessment of the world's possible pathways to 1.5°C, there has been rapidly growing recognition of the crucial role for technologies which can remove CO_2 from the atmosphere.[2] This capability will be essential for balancing any residual greenhouse gas emissions in a net-zero world, where some sectors – such as aviation – remain technically, economically, or socially difficult to decarbonise. In addition, given that the world is far from on track for meeting a target of net zero by 2050, net negative emissions will need to continue well into the second half of the century to bring atmospheric CO_2 concentrations to levels in keeping with the targets set out by the Paris Agreement.

The geological storage of CO_2 can be used to deliver carbon removals when the stored CO_2 is extracted directly from the atmosphere (direct air capture) or derived from biogenic waste or other climate-beneficial forms of biomass, known as bio-energy carbon capture and storage. In the IEA's 'Net zero by 2050' roadmap for the global energy sector, these options combined reach 1.9 Gt CO_2 per year, of which around two thirds is associated with bio-energy.[3] As it currently represents a lower-cost option, the biomass-based pathway is expected to dominate in the near term, but direct air capture is likely to be an increasingly important complement as climate-beneficial sources of biomass become more scarce.

The expansion of nature-based carbon sinks such as forests or increasing soil carbon content can play an important role as short-cycle removals (decades to centuries) which can be rapidly scaled up in the near term. However, the geological storage of CO_2 offers the potential for long-cycle removals (on the order of millennia) with a greater degree of certainty, given that forests and soils are exposed to the risk of CO_2 release from fires or land-use change. Natural sinks also eventually become 'saturated' over time, meaning they stop providing additional net removals. With these limitations in mind, the geological storage of atmospheric CO_2 is best suited to balancing remaining fossil emissions at net zero.

The key policy challenge for driving any kind of carbon removal activity is the need to establish a rigorous certification mechanism that can verify each ton of CO_2 removed and implement a framework for monitoring and reporting. Such a system should aim to reflect the varying attributes of natural and technology-based removals, while ensuring all approaches can demonstrate additionality and verifiability.

As traditional 'offset' credits – often based on the reduction of emissions – are increasingly seen as inadequate in the context of net zero goals, there is a growing voluntary corporate demand for carbon removals on dedicated marketplaces using various certification standards.[107] A leading example of this trend is Microsoft, which has pledged to balance all its current and historical emissions with removals by 2030 and established stringent criteria for which activities count as high-quality CO_2 removals.[108] Voluntary demand is providing a business case for several early-mover removal-based projects in Europe, such as the relatively small-scale direct air capture plant 'Orca' in Iceland, which captures and stores 4000 tCO_2 per year.[109]

Building on the growing societal demand for removals, there is an urgent need for governments to take a leading role in establishing harmonised criteria which can be used as the basis for project funding, compliance markets, and transparent accounting at the sectoral and national levels. Through its release of a communication on 'Sustainable carbon cycles' in December 2021, the European Commission set out its intention to develop an EU-wide Carbon Removal Certification Mechanism, as well as proposing a target of 5 Mt of reaching technological removals by 2030.[110] The UK government has also conducted a public consultation on this issue, with policy outcomes expected in 2022.

With an appropriate accounting mechanism in place, governments must decide how best to incentivise removals through tools such as funding initiatives or regulatory requirements. In Europe, a principal consideration is the extent to which removal crediting should be linked to existing climate policy such as the ETS or the Effort Sharing Regulation, which sets decarbonisation targets for sectors not covered by the ETS.[111,112] Currently there is also uncertainty over whether removal projects will be able to claim parallel revenue both from government incentives and voluntary markets.

Fundamentally, policy must find the right balance between scaling up removal technologies on schedule to reach net zero, and ensuring emissions reductions are prioritised wherever possible. Some technology-based removals, such as the capture and storage of existing biogenic carbon emissions, can be achieved at similar costs to industrial carbon capture and storage, and could therefore potentially be driven by crediting linked to existing carbon pricing. However, direct air capture carries much higher costs (estimated at 190 to 660 €/t) and will therefore need dedicated funding schemes if it is to become a viable option in future.

At the national level, some countries have already moved to establish targeted incentives for certain removal technologies. Notably, Sweden plans to pioneer incentives for bio-energy carbon capture and storage, having allocated SEK 36.3 billion (€3.35 billion) to a subsidy scheme over the period 2026 to 2046.[113] Using a reverse auction process, the scheme will award 15-year contracts to the most competitive projects, starting with a 2022 auction for contracts beginning in 2026 (*see case study below*). In the UK, £100 million in innovation funding has been allocated to support removals based on geological storage, and a new business model for greenhouse gas removals is currently under development.[114]

As a global leader on climate policy, the approaches taken by the EU on certification and funding of removals is likely to set an important example for similar initiatives in other jurisdictions.

Recommendations

- Ensure a broad portfolio of carbon removal options is established for Europe, while moving progressively towards methods with a higher degree of permanence
- Ensure that the EU's forthcoming certification mechanism is based on a full life cycle analysis and minimises uncertainties around permanence and leakage
- Establish targeted fiscal and funding mechanisms at the EU and national level, such as contracts for difference, to support the early development of technology-based removals with geological storage
- Set scientifically informed targets for technology-based removals to be achieved by key milestone dates
- Set biomass standards that encourage the use of waste biomass feedstocks and limit new land clearing

Project case study: Stockholm Exergi's BECCS@STHLM

Stockholm Exergi is a Swedish energy utility which provides heat and power to the country's capital with several waste and biomass-fired cogeneration plants. In 2019, the company installed a small test capture plant on its 375 MW Värtan KVV8 biomass-fired plant, as a first step towards implementing full-scale capture on the plant amounting to 800,000 tonnes of CO_2 per year. With this large-scale bio-energy carbon capture and storage project (BECCS@STHLM), Stockholm Exergi aims to become the first major supplier of negative emissions in Europe. The biomass used by the plant is mostly from chopped branches and treetops produced by sustainable forestry, as well as waste from the pulp and paper industry.[115]

The full-scale project will use the hot potassium carbonate CO_2 capture technology, which has been used for decades in enhancing the purity of Stockholm's gas supply. By using waste heat from the capture process to augment the plant's production of steam for district heating, there is effectively no net energy penalty to the system. The CO_2 will then be compressed, dried and liquefied for transportation by ship to a long-term storage site. The company is in negotiations with providers of storage space on the Norwegian continental shelf.

In November 2021, the proposal received a major boost from its selection by the EU's Innovation Fund for large-scale projects, which provides significant capital and operational funding to decarbonisation projects. However, for the project to be viable, this funding must also be supplemented by Sweden's forthcoming subsidies for negative emissions, which will be awarded through a reverse auction process from 2022, as well as income from voluntary offset markets.

The project plans to make a final investment decision in 2023 and could be operational from 2026. By rolling out a similar process across the company's whole heat and power plant fleet, Stockholm Exergi estimate the potential to capture 1.7 Mt of biogenic CO_2 by 2045.

SECTION 10

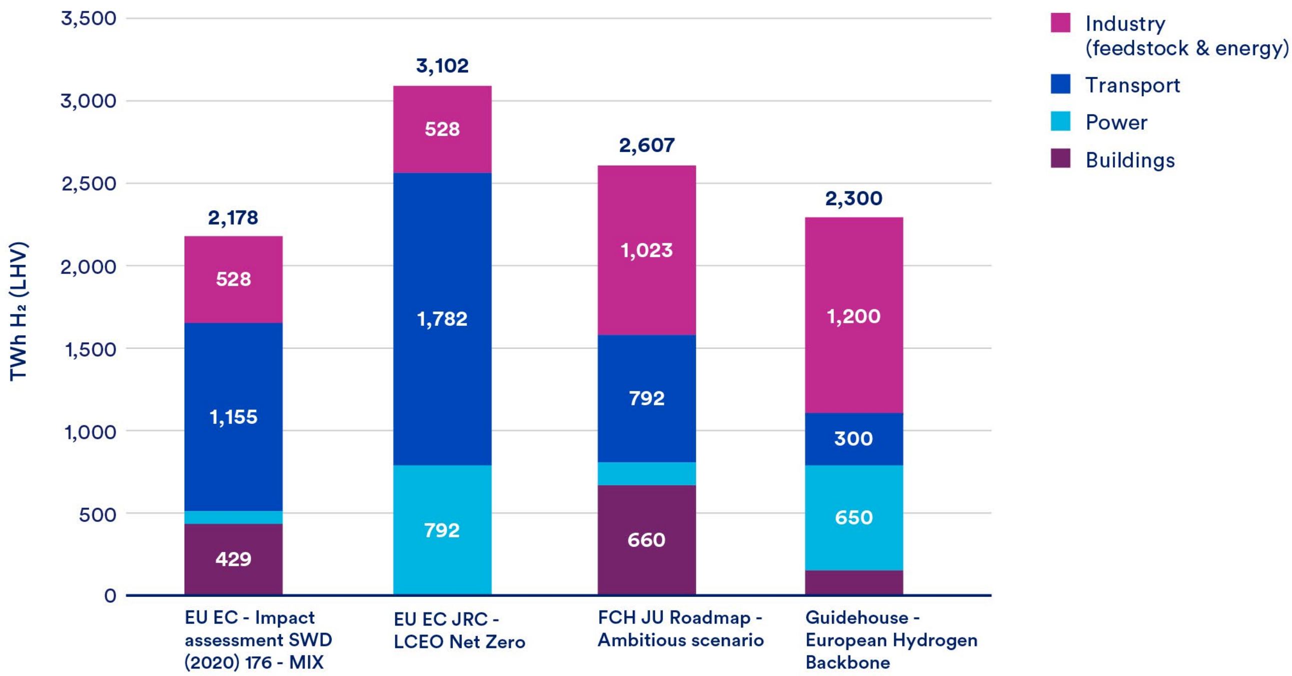
Creating a market for low-carbon hydrogen

The energy system in a net-zero world will rely not just on low-carbon electricity, but on low-carbon fuels. Unlike electricity, energy in the form of fuels can be easily stored, can deliver high-temperature heat needed for many industrial processes, and offers the high-energy densities necessary for many forms of transportation. Today, 80% of global end-use energy consumption is in the form of fuels and, while electrification of many sectors – particularly passenger vehicles – is expected, aviation, maritime shipping, heavy-goods vehicles and industrial processes such as steel production will continue to rely on fuels. In most plausible scenarios for achieving net zero, hydrogen (or its derivatives, such as ammonia) fulfils this role, reaching 530 Mt of annual production in the IEA's 'Net zero by 2050' scenario – a six-fold scale-up from today's production and equivalent (in energy terms) to around a third of global oil consumption in 2019.[3] The EU's 2020 hydrogen strategy outlines an ambition to establish 40 GW of renewable hydrogen production capacity by 2030 (or up to 10 Mt per year), while the UK targets 10 GW by the same date.[54,116] Several studies project that the EU could need at least 2100 TWh (>60 Mt) of hydrogen per year by 2050 (**Figure 20**).[125]

The production of hydrogen via the electrolysis of water with decarbonised electricity is an important pathway but, currently representing 0.03% of dedicated hydrogen production (30 kt H_2 per year), it cannot meet the scale of the task alone.[117] Low-carbon hydrogen can also be obtained by reforming natural gas and safely storing the CO_2 produced by this process. Already producing 700 kt per year of hydrogen, this process is much more established today than the electrolysis route and could be rapidly scaled up in Europe. For this reason, decarbonisation pathways such as the IEA's 'Net zero by 2050' and the UK's Net Zero Strategy feature significant expansion of this form of hydrogen, particularly to meet near-term demand.

Just as for other low-carbon products, developing a market for low-carbon hydrogen requires governments to establish appropriate certification and carbon accounting protocols. Determining the acceptable carbon intensity of hydrogen is complex, both for the electrolysis and natural gas-derived products, requiring a full life cycle analysis, monitoring and verification. Upstream methane emissions are potentially the most

Figure 20: Projections of potential hydrogen demand in 2050 according to four EU decarbonisation studies[125]



significant contribution to the climate impact of natural gas-derived hydrogen, so must be rigorously accounted for with robust measurement and emissions reporting and kept as close to zero as possible.

A few voluntary pilot schemes for the certification of low-carbon hydrogen have emerged in recent years, including the EU-wide 'CertifHy' scheme developed by a consortium of industrial hydrogen producers and consumers, which defines a Guarantee of Origin for 'Green hydrogen' (from electrolysis with renewable energy) and 'Low carbon hydrogen' – defined as hydrogen with at least 60% lower greenhouse gas emissions intensity relative to a benchmark.[118] Other standards are under development at the national level in the UK, France, and Germany (electrolytic hydrogen only), and by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).[119] In a recent proposal to revise EU legislation known as the Decarbonised Gas and Hydrogen Package, the Commission defined low-carbon hydrogen as meeting a 70% reduction in greenhouse gas emissions relative to unabated fossil hydrogen.[120] However, the Delegated Act providing details of the accounting methodology and certification system to support this standard is not expected until 2024, creating uncertainty for project developers in the meantime and potential conflict between the emerging voluntary and national standards.

Now, there is an urgent need to begin developing the Europe-wide transport infrastructure for a future hydrogen economy, and this will only be realised if large volumes of low-carbon hydrogen are made available in the near-term. Carbon intensity targets for hydrogen should therefore take into account a role for hydrogen decarbonised with carbon capture and be designed to allow for gradual tightening of acceptable carbon intensities over time. Electrolytic hydrogen production must also be rapidly deployed but, given that over 35% of the EU's electricity still comes from fossil fuels, renewable electricity remains a precious resource.[121] For electrolytic hydrogen to meet the EU's proposed 2030 targets for the use of non-biological renewable fuels in industry and transport, 500 TWh of additional renewable energy will be required per year – around half of the region's annual renewable output.[122]

While stimulating demand for low-carbon hydrogen, along with appropriate certification, can help drive investment in new hydrogen production with carbon capture, these facilities may still require additional incentives at today's carbon price levels. Two of the CO_2 capture plants supported by the Dutch SDE++ scheme under the Porthos project are associated with existing hydrogen production, however, new facilities to produce hydrogen for fuel applications are not viable under the SDE++ in its current form. For hydrogen to take on its anticipated role as an energy vector of the future, such incentives should consider also supporting production of the gas for fuel uses. In the UK, a contract for difference model tailored to new hydrogen plants is currently being developed.

Developing the hydrogen pipeline network necessary for a hydrogen economy will bear many synergies with the deployment of CO_2 transport networks. Both networks will primarily need to link major industrial areas and ports, bearing in mind that the several Member State's ambitions for hydrogen also include plans for large-scale imports. Both networks will be able to reuse existing gas pipelines and transport corridors, but they will both require new regulatory regimes, cross-border planning, and coordination at the regional and EU level. The European Hydrogen Backbone is an initiative led by gas infrastructure companies that has mapped out a 6800 km pipeline network which could be in place by 2030, including potential hydrogen storage sites.[123]

Recommendations:

- Establish a robust certification scheme for low-carbon hydrogen based on life cycle analysis and with provisions for import and export between jurisdictions
- Thresholds used to define low-carbon hydrogen should be ambitious – including upstream standards for methane leakage – and adaptive to technology developments
- Grant low-carbon hydrogen-as-fuel projects eligibility to support schemes for emissions reduction projects
- Regional planning and coordination of hydrogen transport network development with CO_2 networks

Project case study: H-vision

H-vision is a plan to develop hydrogen production and transport infrastucture for industries in the Port of Rotterdam, based on the conversion of refinery exhaust gases (made up of hydrogen and light hydrocarbons) and the capture and storage of the CO_2 produced. The resulting low-carbon hydrogen will be returned as a fuel for the refineries and other industrial process requiring high-temperature process heat – replacing the previous CO_2-intensive use of the exhaust gases as a fuel. Established in 2019 by ten industrial partners and the Port of Rotterdam, the H-vision consortium aims to cut 2.7 Mt of CO_2 emissions in the port by 2032, and is currently in a pre-FEED phase.[124]

An initial hydrogen plant with a capacity of 750 MW is planned for start-up in 2026, followed by a second unit of similar size by 2032. These units convert a feed consisting of around 90% refinery exhaust gases supplemented with less than 10% natural gas. The first phase of the project also intends to invest in a local hydrogen network, which would connect to a wider national initiative to establish a hydrogen 'backbone' pipeline in Rotterdam and beyond. Ultimately, it is envisaged that the hydrogen infrastructure could be adopted for 'green' hydrogen produced from electrolysis, either from within the Netherlands or imported from countries with low-cost hydrogen supply. While the production of hydrogen for fuel is not supported by industrial decarbonisation funds under SDE++ scheme, the project has struggled to establish a business case. However, the 2022 allocation of the scheme is set to include a new category for the production of hydrogen from residual gas streams, which could provide a route for H-vision to progress.

SECTION 11

Addressing barriers to a flexible and international market

Although Europe is blessed with suitable CO_2 storage geology throughout most of the continent, there is nevertheless a disparity in resources which has been further accentuated by the early focus on developing the North Sea. Many of the capture-based projects and clusters currently proposed are planning to send CO_2 to storage sites in other countries – usually Norway or the Netherlands, but potentially to storage sites in the UK, Denmark, or France in future. Even as more storage sites are developed across Europe, there is a fundamental benefit from enabling a flexible international market in which emitters can choose to send CO_2 to the most competitive storage site, or simply to be able to divert their emissions should the usual site not be operational.

Unfortunately, the transport of CO_2 across international borders, even within the EU, still poses a significant barrier to rapid project development, owing to an international environmental law known as the London Protocol.[126] Governing the maritime disposal of waste materials, this legislation has included provisions for the safe injection of CO_2 beneath the seabed since 2006, but it still formally prohibits the export of CO_2 for disposal in another country. In 2009, an amendment to this restriction was proposed and adopted by vote, but does not officially come into force until it is ratified by at least two thirds of the contracting parties to the Protocol; so far, only six of these countries have signed (Norway, the Netherlands, the UK, Finland, Estonia, and Iran). To circumvent this impasse, a provisional solution was reached in 2019, whereby two countries could reach a bilateral agreement to permit the export and import of CO_2 for offshore storage; a solution which has proved crucial for the development of Northern Lights.

However, this issue remains a hurdle for many projects, as to date, only the Netherlands and Norway have reached such a bilateral agreement. Negotiations to reach such an agreement can be time-consuming and lead to project delay and uncertainty. A key issue is the transfer of liability between countries, as the storing nation may be reluctant to bear the entire liability for CO_2 which it has not itself emitted. This may extend to the costs of monitoring a storage site once it has been transferred to the state, or the risk of paying future carbon costs for leaked CO_2. Although these costs and risks are considered small, they can nevertheless complicate a swift conclusion to a cross-border agreement. Here, there is a clear role for the EU in providing a set of guidelines or template for fair agreements between countries, helping to avoid a regulatory patchwork which could limit market liquidity.

Given the long deployment times and large volume flows required for pipeline infrastructure, it is crucial that legislation and technical and regulatory coordination should not neglect the role of more flexible transport options such as ship, rail, and road tankers, which can catalyse carbon capture development at smaller, dispersed sites. Developing international transport networks encompassing all these modalities will require close cooperation between relevant entities in different member states, including gas network operators, shipping and rail companies, and port authorities. To ensure mutually compatible and scalable infrastructure is developed, the EU should also work with standardisation bodies to develop acceptable standards for CO_2 specifications such as temperatures, pressures, and allowable concentrations of contaminants for the various transport modalities and storage sites.

Recommendations:

- Include all CO_2 transport modalities in the revision of the EU's TEN-T regulation
- Develop a Europe-wide set of CO_2 specification standards for transportation by pipeline, ship, road and other modalities, together with guidance on acceptable specifications that can be required by storage sites
- Establish a platform for close coordination between regional CO_2 transport network operators, including those associated with pipelines, terminals and other modalities
- Encourage member states to ratify the amendment to the London Protocol
- Establish guidelines or a template for reaching bilateral agreements on the cross-border transport of CO_2

Cross-border network case study: Carbon Connect Delta

Carbon Connect Delta is an emerging plan for a shared carbon transport infrastructure for the North Sea Port – a cross-border port authority encompassing the Dutch ports of Vlissingen and Terneuzen and the Belgian port of Ghent.[46] The project was launched in 2020 by the regional industrial group Smart Delta Resources, which formed a consortium from a subset of its members, including the North Sea Port authority, Dow Benelux, PZEM, Yara, Zeeland Refinery, Gasunie, and Fluxys. The consortium aims to cut CO_2 emissions from the area by 30% (6.5 Mt of CO_2 per year) by 2030 through the use of CO_2 capture, utilisation and storage, with close links to parallel plans to develop hydrogen production and transportation infrastructure.

The emitting industries identified as likely 'first movers' in the region include the Yara fertiliser plant and Dow's chemical production site in Terneuzen and the Zeeland Refinery across the Scheldt estuary in Vlissingen. These sites could capture and store up to 3.3 Mt CO_2 per year from 2026. ArcelorMittal is also pursuing CO_2 capture for its blast furnace in Ghent: under the 'Steelanol' project, carbon monoxide in the exhaust gases is converted to ethanol, leaving 300,000 tonnes of CO_2 for geological storage.

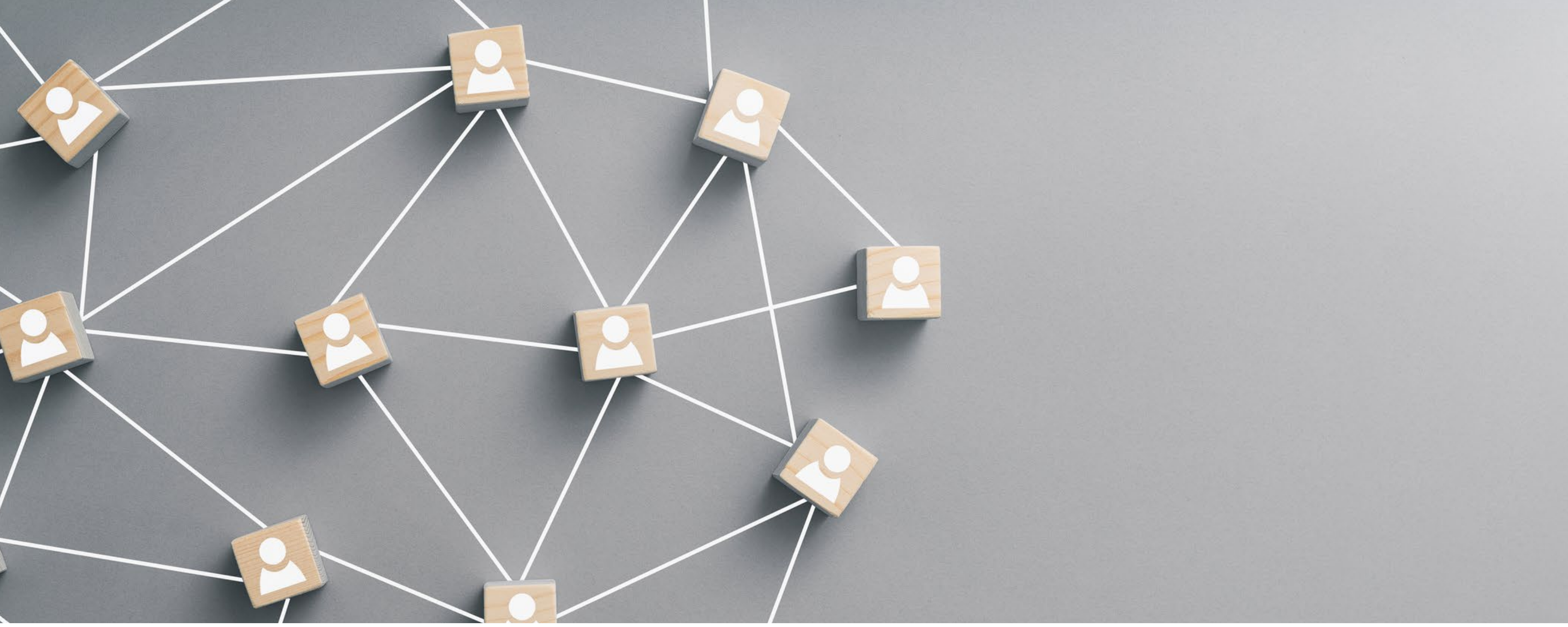
Early work by Carbon Connect Delta has assessed the different CO_2 transport options available, selecting CO_2 shipping as the most promising solution for the first phase of the project. This is likely to involve a

Figure 21: The region covered by the North Sea Port

centralised collection point and export terminal, with an internal transport infrastructure, such as barges or pipelines to link the various emitters. Given the constraints of the Dutch SDE++ system, which currently requires CO_2 to be stored within the Netherlands, the CO_2 will initially be shipped to Rotterdam where it can feed into storage sites associated with the Porthos or Aramis projects. Carbon Connect Delta also forms part of the cross-border CO_2 network PCI known as CO2TransPorts, which plans to develop CO_2 linkages between the ports of Rotterdam, Antwerp, and the North Sea Port. The first phase of this initiative (from 2024) is focused on developing the Porthos infrastructure, but a second phase (from 2026) aims to establish a CO_2 pipeline network in the Antwerp and North Sea Port area.

Carbon Connect Delta faces several challenges related to the cross-border nature of the cluster itself. The Dutch emitters are considered the project's first-movers due to their eligibility for the national SDE++ scheme, with the expectation that Belgian emitters could use future funding opportunities to join an established transport network. Without close alignment between national or regional subsidy schemes, it is highly challenging for cross-border emitters to form a cohesive plan which can move towards a final investment decision together. This introduces an additional element of uncertainty and risk to the 'coordination challenge' outlined above. Issues surrounding barriers to cross-border transport of CO_2 are also present within the cluster, including the current lack of bilateral agreement between the two countries (Belgium is working towards ratifying the amendment to the London Protocol).

As industrial decarbonisation clusters develop and expand around Europe, the cross-border issues faced by Carbon Connect Delta will become more common. Greater alignment of technical standards, regulations, and subsidy schemes between European states can help remove these potential barriers and allow infrastructure to develop in a cost-optimised manner.



SECTION 12

Building broad stakeholder support

Previous efforts to deploy carbon capture in Europe have highlighted that it is critical for projects to work carefully to build the support of the public and other local stakeholders. Poor communication and other local factors led to strong local opposition and the eventual cancellation of some early proposals in the Netherlands and Germany. Ultimately, the public loss of trust in industrial developers, deepening divisions, and the associated political response, have had long-term consequences for the technology in these countries and others: CO_2 storage was effectively banned in Germany and Austria, and onshore storage banned in the Netherlands. While carbon capture (with offshore storage) has returned to the political agenda in the Netherlands, support from the public and environmental NGOs remains fragile. To help alleviate concerns, the 2018 Climate Agreement placed a cap on the amount of carbon capture which could be subsidised. However, the raising of this cap without consultation in 2021 drew objections from civil society, emphasising the need for carbon capture policy to be backed by clear communication and dialogue.

Although experiences in the Netherlands and Germany have cast a long shadow on current developments in Europe – particularly for onshore storage – many earlier initiatives met with much greater acceptance. Previous proposals to develop carbon capture in North-East Scotland have generally enjoyed good public support, helped by considered communication strategies and a local population with close ties to the oil and gas industry and an understanding that it must evolve. Research-based projects have generally also met with greater public acceptance, even when injecting quite significant quantities of CO_2 in onshore areas, such as the Lacq, Hontomin, and Ketzin projects.[75,127,128] This demonstrates that it is often not the activity itself which necessarily raises public concern, but the lack of trust in emitting industries, coupled with the perception that carbon capture and storage is merely an excuse to continue 'business as usual'. On the other hand, support for climate change action and investment in Europe is generally relatively high and is, in many regions, coupled with growing concerns over the future of local industries and jobs.

Project developers must put in place good stakeholder communication and engagement strategies, while building coalitions with more trusted backers such as local governments, supportive NGOs, and research institutes. Cluster decarbonisation efforts may even be coordinated and initiated by such 'local champions', external to the emitting industries themselves (*see box on Pycasso project*). But there is also a vital role for national governments and the EU to support industry efforts to decarbonise by delivering a clear, unequivocal message that carbon capture and storage is a viable and unavoidable option for rapidly achieving net zero. This can prevent the knowledge imbalance which has characterised many early efforts, where policymakers have recognised the decarbonising value of the technology and supported developments, but public awareness has remained low until projects directly infringe on people's lives. Governments can provide a powerful signal to both the public and investors that the technology will feature in the country's future, particularly if supported by independent, science-based analysis showing the contribution carbon capture must make towards decarbonisation goals. As more projects are successfully realised in Europe, they can be increasingly used as tangible evidence of large-scale emissions reductions and safe operation. In short, the responsibility for promoting the idea of carbon capture and storage as a climate change solution cannot be left solely to industry, or it is unlikely to progress at the rate required.

Recommendations:

- Clear, evidence-based messaging from all levels of government on the role for carbon capture and storage in reaching net zero
- Support policy announcements with good communication and public consultation where necessary
- Encourage local governments or other local entities to help coordinate regional decarbonisation clusters

Project case study: Pycasso

Standing for 'Pyrenean carbon abolition through sustainable sequestration options', but with a nod to the cross-border connections of its namesake, the Pycasso project aims to help drive the decarbonisation of industrial emitters on either side of the French-Spanish border.[18] The initiative is rooted in an early CO_2 storage pilot project carried out by Total in the depleted gas field of Rousse, close to the French city of Pau. Between 2010 and 2013, 51 kt of CO_2 from a nearby gas processing plant were injected, with generally good support from the local population. With an estimated 435 Mt CO_2 capacity in this reservoir, as well as more in other gas fields nearby, the region is among the most promising storage sites in France.

From its conception in 2021, the vision of Pycasso has been to put this storage resource at the heart of a cross-border industrial cluster, developing a broad coalition of emitters on either side of the Pyrenees. In total, 13 Mt/year of CO_2 emissions are covered by the initial plan (5 Mt in France and 8 Mt in Spain), associated with chemical production, oil refining, paper, waste incineration, and cement. These industries have signed MoUs to help develop the concept, forming a consortium which also includes local academic universities and regional government; the French local government of Pau Béarn Pyrénées (close to the storage site) is also a member of the project steering committee. The presence of a regional government as a local champion for the project has been identified as a key factor in gaining the trust and support of the public and other local stakeholders. Driving this close partnership is the region's ambitious goal of achieving climate neutrality by 2040, combined with the local authority's realisation that the challenge of decarbonising industry dwarfs any measures to reduce the carbon footprint of individual citizens.

The availability of well-developed, onshore storage in the region offers the potential for highly competitive overall costs for carbon management deployment, with one independent study estimating a total 'stored' cost of €69/t (based on a standard post-combustion capture process), making it the lowest cost region assessed in France. The cluster may also be able to repurpose existing gas pipeline infrastructure and is currently assessing this possibility, for both CO_2 and hydrogen transport. Further in the future, the port of Bayonne offers the potential for CO_2 imports.

The project plans to apply for further development phase funding through the EU's Horizon Europe fund, with plans to conduct a detailed engineering study from 2022. A positive final investment decision in 2024 or 2025 could lead to first CO_2 injection in 2027 and potentially full operation of the cluster by 2030.

SECTION 13

Summary: a technology policy framework

Analysis for CATF by Element Energy estimates that up to 1.5 Gt of CO_2 emissions may need to be captured and stored each year in Europe by 2050 in order to meet the net zero goal.[129] Although several countries are now making rapid progress on carbon management technologies, this report highlights some of the challenges faced if this level of widespread deployment is to be reached in the necessary timescale. Many of these barriers can be identified as a shortage of key 'success factors' for rapid technology deployment (**Figure 22**).

Figure 22: Success factors for development of carbon capture and storage in Europe

SUCCESS FACTORS

Lower Cost

- Support technology demonstration in less advanced sectors
- Prioritise low capital, easily replicable technologies with scalable supply chains

Fast project deployment

- Standardised, modular technologies for rapid roll-out
- Reduce permitting times for CO_2 storage with a standard approach
- Repurpose existing infrastructure
- Self-activating support policies

Easy access to financing

- Build investor confidence with clear policy commitment and targets
- Adapt existing, well-understood support mechanisms
- Address challenging infrastructure risks: coordination and leakage

Ecosystem challenges

- Public-private partnerships for infrastructure development and coordinated expansion
- Finalise regulatory framework for CO_2 storage where still absent
- Eliminate cross-border transport barriers
- Build public support with trusted, independent messaging

It is eminently possible to overcome these hurdles and create a sustainable policy framework in which carbon capture and storage can flourish. This is being demonstrated today by those European states which have resolved to deploy CO_2 storage infrastructure in the 2020s, having identified an unavoidable need for these technologies to meet their climate goals. While each of these countries is forging a unique approach consistent with existing energy policy frameworks and local priorities, their shared success factors are clear. Direct government funding is essential at this early stage, particularly to rapidly develop the enabling transport and storage infrastructure which will provide a signal to emitting industries and enable incremental future expansion at lower cost. Public-private partnerships along the carbon management value chain can help reduce early project risks and help ensure that infrastructure expands ahead of CO_2 availability, rather than lagging behind emitter demand.

Governments also need to establish an investable business case for emitters wishing to capture their CO_2, just as similar guaranteed revenues have supported rapid renewable energy deployment in many countries. This does not necessarily imply direct project funding, but could include exposing emitting sectors to a guaranteed carbon price. However, the structure of these incentives will depend on local energy policy and, where possible, building on existing, successful decarbonisation mechanisms is an effective means of helping to attract larger-scale, risk-averse investors and shortening implementation periods.

In time, targeted support mechanisms can fall away as carbon price signals become stronger in accordance with the net zero goal, together with growing public and private sector demand for low-carbon products and services (**Figure 23**). With this progression in mind, policies which are implemented today to kickstart the sector will benefit from adaptability and repeatability in a high-carbon price context, allowing levels of competition to gradually increase and levels of government support to decrease. Some forms of targeted support, such as incentives for CO_2 removals, will need to evolve over time to harmonise with wider carbon pricing systems.

Wind and solar power are technologies that have recently passed through these development stages, with wind reaching around 1% of global primary energy consumption and solar providing around half that contribution. Figure 24 indicates the scale of historical and current levels of global investment in renewable energy – representing largely wind and solar – which has been required to bring about its remarkable expansion over the past two decades.[130] In 2020, the nearly $300 billion of investment into these technologies was a hundred times the total global investment towards carbon capture and storage. The contribution of government finance required to support the rise of renewable energy has been significant, but has been able to decline over time as the sector has been derisked for large-scale, private investment. With the right policy support, large-scale investment in carbon capture and storage can also be unlocked over the coming decade, and can bring similar returns in terms of CO_2 abatement. In Europe, total solar and wind power output in 2019 avoided 74 Mt and 227 Mt of CO_2 emissions respectively (assuming only gas power is displaced), while announced carbon capture projects alone promise to avoid upwards of 80 Mt per year by 2030.

Figure 23: The evolution of carbon capture and storage innovation policy over different stages of development

Research & Development

- Focus on easily standardised, modular technologies
- New sectoral applications

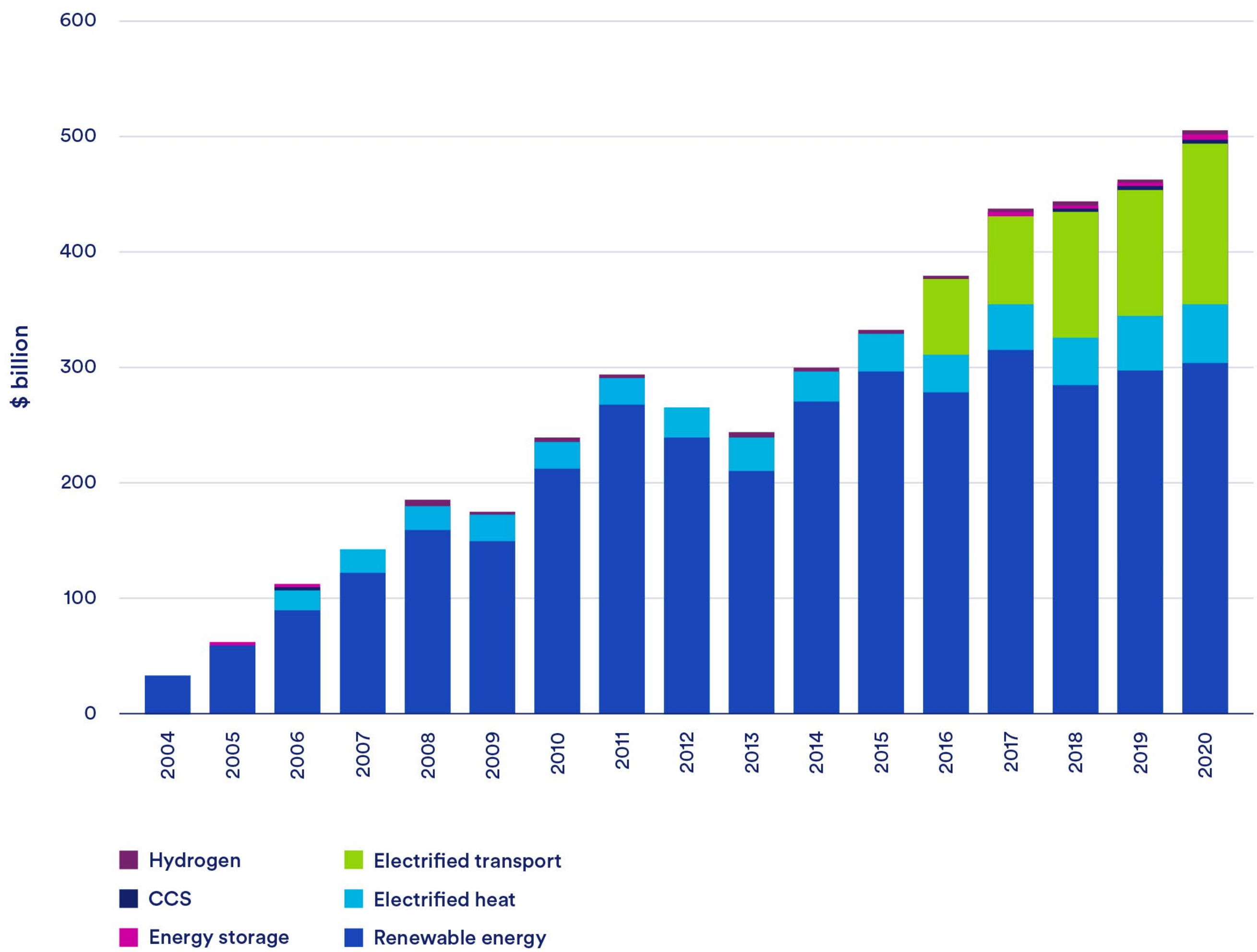
1st-Nth Plant

- Carbon price 'top-up', e.g. CCfDs
- Targeted support for scalable CO_2 capture
- System-oriented investment in storage and infrastructure development
- Governments sharing some project risks

Expansion

- High carbon price
- Consumer demand for low-carbon products
- Competitive and flexible CO_2 storage
- Market for carbon removals

Figure 24: Global investment in energy transition technologies by sector (Bloomberg, 2021)[130]



SECTION 14

Taking a long-term view: an EU strategy for carbon capture and storage

What sets apart those European countries that are currently most committed to successfully implementing carbon capture, removal, and storage? Most obviously, the availability of tried and tested CO_2 storage geology in the North Sea, has presented an opportunity to countries with established offshore industries in this region. However, these countries have also been confronted with the manifest need for a carbon capture and storage strategy if they are to reach the uncompromising goal of net zero. Every emitting industry will need a decarbonisation solution to remain viable, preserving vital jobs and economic activity and avoiding carbon leakage from production shifting to other parts of the world.

Where policy has been directly informed by long-term analysis to net zero, the role of carbon capture becomes inescapable, owing to its role in decarbonising hard-to-abate industries and in enabling the atmospheric removals to offset even more challenging emissions. In the UK, the Climate Change Committee – an independent body which advises on the binding long-term carbon budgets set by government and the steps needed to reach them – noted that carbon capture and storage is 'a necessity and not an option'.[131,132] In Sweden, a similar long-sighted approach, coupled with a more ambitious net zero target and informed by a Climate Policy Council, has highlighted a need for engineered carbon removal solutions.[133] Denmark's recent turnaround on carbon capture also stems from more ambitious reductions (70% by 2030) and long-sighted government analysis of the steps necessary to achieve them.[134] In Germany, analysis by independent entities such as Agora, Ariadne, and Dena in the last year have also signalled a need for CO_2 capture (ranging from 29 to 74 Mt per year) if the country's goal of net zero by 2045 is to be met.[135]

The growing role for carbon capture and storage under a longer-term perspective is further highlighted by the number of countries including the technology in the Long-term Strategies they have submitted under the UNFCCC Paris Agreement; this is the case for 20 European states including France, Belgium, Spain, Austria, and the Czech Republic. And yet, this is not a climate solution for which action can be delayed, whether it is needed now or in two decades. For it to be a viable option for industry in any country by the 2030s and 2040s, supporting infrastructure needs to be put in place today and capture technologies need to be deployed early to deliver cost-optimised processes when they are needed at large scale.

The clarity provided by this long-term, 'whole system' analysis approach can in turn lead to policy clarity on the role, scope, and longevity of carbon capture and storage. Deployment targets are a powerful means of signalling reliable political support, having already been used to great effect in attracting investment in the renewables sector. Similar targets for industrial carbon capture and permanent CO_2 removals are needed to rebuild industry and investor confidence which has severely waned following failures of previous European efforts to support these technologies.

The European Commission can take a leadership role in clarifying the importance of carbon management technologies for achieving the region's ambitious climate targets, while decarbonising all sectors and preventing the loss of valuable economic activity and livelihoods. This renewed commitment should be set out in an EU strategy document which outlines the long-lasting role and scope for the technology in the region and identifies areas where new or amended legislation is required.

Such a strategy should:

- Set clear milestone targets based on scientifically sound long-term modelling of economy-wide decarbonisation and a climate risk minimisation approach:
  - Mt of CO_2 which should be stored by milestone dates (2030, 2040, 2050)
  - Mt of carbon removals, including secure geological storage of atmospheric CO_2
- Develop a plan to identify, characterise, and permit strategically placed large-scale storage sites around the region, based on Member State submissions of prospective capture and storage volumes
- Coordinate relevant EU legislation and EU funding with Member State initiatives
- Establish a position on the appropriate manner of regulation of the emerging market for CO_2 storage, aimed at avoiding monopoly power, stimulating competition, and encouraging adequate expansion
- Develop an overarching plan for the development of optimised cross-border CO_2 transport infrastructure, including the identification of corridors for trunk pipelines and solutions for dispersed emitters (ships, road tankers, rail, and barges)
- Establish a Europe-wide regulatory platform for CO_2 transport infrastructure, including CO_2 specifications
- Guidelines from the Commission to encourage all Member States with plans to capture or store CO_2 to ratify the amendment to the London Protocol on CO_2 transportation and to address remaining regulatory gaps on CO_2 storage
- Create a regional coalition to ensure the North Sea Basin is developed on schedule to deliver on the order of 1 Gt of storage by 2050
- Provide guidelines on how to work with non-member states (particularly Norway and the UK) to develop a common approach to CO_2 transportation and storage which allows for the North Sea to realise its potential as a shared storage resource
- Establish a dedicated European forum on carbon capture and storage for coordination between relevant stakeholders, including thematic working groups to develop international guidelines, promote knowledge and technology transfer, and identify shared business opportunities

Not all Member States may choose to store CO_2 within their jurisdictions, or to include carbon capture and storage as part of their decarbonisation strategies; this will ultimately depend on local context including geology, availability of renewable energy, existing industrial sectors, and other local priorities. However, the EU can deliver a clear message that carbon capture does represent a viable option for decarbonising hard-to-abate sectors and offer support to those countries wishing to develop their own CO_2 storage or allow their emitters to connect to cross-border sites. This will ensure that these technologies remain an equitable, open-access solution for all who require them to decarbonise.

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