Preface

To be added in final draft

Executive summary

To be added in final draft

Definitions

- *CCS consists of the capture of carbon dioxide (CO_2) from e.g. industrial installations or directly from the atmosphere, its transport and injection into a suitable underground geological formation for the purposes of permanent storage.*
- *CCS directive* meaning "Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance)"
- *CCU – the utilisation of captured CO_2 where the CO_2 is permanently chemically bound in a product so that they do not enter the atmosphere under normal use and disposal.*
- *Carbon dioxide removal – the process of permanently removing CO_2 from the atmosphere*
- *BECCS – bioenergy with carbon capture and storage*
- *DAC(S) – direct air capture (and storage)*
- *IAM – integrated assessment model*
- *TRL – technology readiness level*
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Introduction and scope

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

Alongside a range of other low-carbon technologies, including renewable energy, energy-efficiency, and zero-carbon fuels, carbon capture, utilisation and storage (CCUS) is expected to play a key role in realizing global and EU ambitions to reach net zero in this short time frame. CCUS encompasses the suite of processes involved in separating CO_2 from industrial emissions or from the atmosphere, followed by permanent storage either in deep geological formations or in the form of products such as carbonates. Owing to the wide variety of decarbonised services these technologies can provide to society (see below), energy system modelling consistently emphasises that CCUS will be essential in achieving net zero within the necessary timeframe and at lowest overall cost (Table 1). The European Commission's modelling of scenarios consistent with 1.5°C of warming indicates that between 280 and 600 Mt of annual CO_2 capture will be required within the EU by 2050[3] (Table 1, Figure 1). This is broadly consistent with other assessments such as the IEA's 'Net zero by 2050' scenario, which includes 7.1 Gt of CO_2 stored per year globally by 2050 (of which around 350 Mt/year is in Europe) or DNV's 'Pathway to Net Zero', which features over 570 Mt of CCUS in Europe by 2050. Of the Integrated Assessment Models presented in the IPCC's 6th Assessment Report indicates, there is a median 665 Gt of CO_2 captured and stored globally by 2100 across 1.5°C compatible scenarios and,[4] of seven 'Illustrative Mitigation Pathways', the only pathway without CCS deployment also requires a nearly 50% drop in primary energy consumption by 2045.

Table 1. Estimates of CO_2 capture required in Europe by 2050

	A clean planet for all (EC, 2018)[5]	**Sustainable Carbon Cycles (EC, 2021)[6]**	**Net Zero by 2050 (IEA, 2020)[3]**	**Pathway to Net Zero (DNV, 2021)[7]**
Total CCUS in 2050 (Mt/y)	606 (1.5Tech) 281 (1.5Life)	550 (INDUS) 330 (ECOSYS)	7600 (Global) ~350 (Europe)	568
Total DAC and BECCS in 2050 (Mt/y)	486 (1.5Tech) 207 (1.5Life)	~330 (INDUS) ~230 (ECOSYS)	1900 (Global)	345 (194 DAC)

1 Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality "European Climate Law"

2 Communication (EU) COM(2019) 640 The European Green Deal

3 IEA (2021) Net Zero by 2050. A roadmap for the global energy sector. Paris, France, International Energy Agency, 224 pp (2021)

4 IPCC (2022) Climate Change 2022: Mitigation of climate change. Working Group III contribution to the IPCC Sixth Assessment Report.

5 EC (2018) A clean planet for all – a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (Nov 2018)

6 EC (2021) Commission staff working document on sustainable carbon cycles (Dec 2021)

7 DNV (2021) A pathway to net zero emissions (Oct 2021).

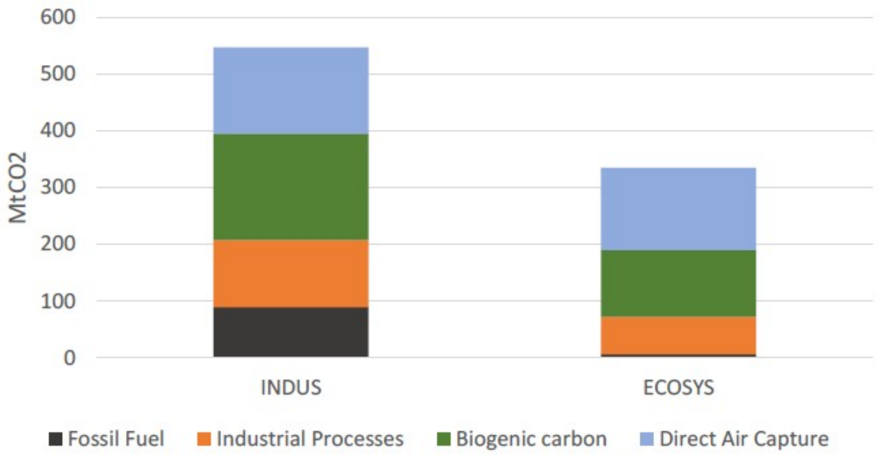


Figure 1. Estimated annual CO_2 capture volumes for the EU in 2050 under two possible scenarios (Sustainable Carbon Cycles, 2021)[6]

Applications for CCUS

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

- CCUS offers a means of mitigating emissions from 'hard-to-abate' process industries, such as cement, steel, and chemical production, where CO_2 is often either emitted as a consequence of the process chemistry, or fossil fuel combustion is essential to deliver the high temperatures required. In 2019, industrial emissions accounted for around a quarter of EU (+UK) CO_2 emissions, and there are currently few options available for deep decarbonisation of this sector.
- In the energy sector, renewable sources are expected to decarbonise a large share of the EU energy consumption by 2050, but dispatchable power plants will likely also be needed to support intermittent wind and solar generation. Hydrogen may be a solution in some cases, but in some regions, fossil fuel-based generating capacity equipped with CCUS may be the optimum solution for this role. As outlined in the EU's Hydrogen Strategy, by decarbonizing the production of hydrogen from fossil fuels, CCUS can also help meet the region's targets for transitioning to low-carbon fuels, particularly in the near to medium-term while electrolytic hydrogen production and renewable electricity is scaled up.
- The geological storage of CO_2 derived from direct air capture (DAC) or bioenergy processes (BECCS) offers a means of permanently removing large volumes of carbon from the atmosphere, provided the biomass consumed is produced in a climate beneficial manner. Climate modelling is clear that these CO_2 removals will be essential, both to balance any residual fossil emissions at net zero, and to bring atmospheric concentrations to acceptable levels by reversing the legacy of historic emissions. Indeed, Commission scenarios consistent with 1.5°C indicates that removals will represent more than half of CCUS deployment by 2050, while the IAMs assessed by the IPCC feature a median of 364 Gt cumulatively stored from BECCS and DACS by 2050.

There is overwhelming evidence that CCUS will be vital in achieving the EU's legally binding target of net zero greenhouse gas emissions by 2050 and can also make an important contribution to the interim target of a 55%

reduction by 2030. This 'Vision' paper aims to outline a long-term strategy for how the EU can ensure that CCUS is developed on schedule to fulfil its decarbonising potential and meet the needs of a climate-neutral Europe. It will outline the EU's vision for CCUS to 2050, proposing targets and policy developments that can create predictability for scaling the component technologies and supporting the pathway towards climate neutrality by 2050.

The paper will cover the range of technologies required to capture CO_2 from point sources and directly from the atmosphere, the CO_2 transport networks required, and the permanent sequestration of CO_2 either in geological reservoirs (saline aquifers, depleted hydrocarbon reservoirs, or basalts) or products. Although likely to also play an important role in future circular economies, the conversion of CO_2 to products in which the CO_2 is re-released as part of normal use (such as fuels or fertilisers) is not considered within the scope of this paper, as no permanent storage of CO_2 results.

From a climate perspective, the extent to which processes which utilize captured CO_2 can contribute towards climate change mitigation depends on the lifecycle of captured CO_2, since only products storing CO_2 permanently are compatible with reaching the target of net zero or climate neutrality by 2050.[8] Hence, processes which utilize CO_2 but do not store it permanently in geological formations, can only be deemed compatible with the EU's target of climate neutrality by 2050 if the CO_2 is permanently chemically bound in a product so that they do not enter the atmosphere under normal use or during that product's disposal. We therefore recommend that a separate strategy document should address the development of these CO_2 use-cases.

The need for a CCUS strategy for the EU

The EU has already taken a number of steps to support the development of CCUS in the region. The CCS Directive of 2009 establishes a regulatory framework for the geological storage of CO_2, which has been implemented in various forms in all Member States. The inclusion of CO_2 storage (and, under the current revision, certain forms of CO_2 utilisation) in the Emissions Trading System, means that ETS-compliant emitters can avoid surrendering allowances by storing CO_2; in theory, providing an economic driver for CCUS. Direct funding for capture and infrastructure project deployment is also available through mechanisms such as the Recovery and Resilience Facility, the Connecting Europe Facility, and the Innovation Fund.

Despite these initiatives, CCUS has progressed slowly in the EU and internationally, often struggling to move beyond 'first-of-a-kind technology' demonstration projects or, in some sectors, even to reach this stage.[9] The IEA's Clean Energy Technology Tracker identifies CCUS in both power and industry as one of several technologies that are 'not on track' to reach net zero.[10] Of more than 26 commercial-scale CCUS projects operating today, most are driven by the use of CO_2 for enhanced oil recovery, and only two are located in Europe – Norway's Sleipner and Snøhvit projects based on the storage of CO_2 removed during natural gas production.

[8] de Kleijne and others, 'Limits to Paris compatibility of CO2 capture and utilization' One Earth 5 (2), 2022 <https://www.sciencedirect.com/science/article/pii/S2590332222000446 >
[9] GCCSI (2021) The global status of CCS: 2021. Melbourne, Australia, Global CCS Institute, 43 pp (2021)
[10] https://www.iea.org/topics/tracking-clean-energy-progress

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

A recent wave of industry interest in CCUS as a decarbonisation tool has led to over 80 new capture or storage projects being proposed in Europe since 2019, but only one (Norway's 'Longship project') has taken a positive final investment decision (FID) and is now under construction. The ability for emitters to make tangible plans to develop CO_2 capture has been in large part unlocked by the near-term promise of available 'open access' storage such as Norway's Northern Lights, which are currently reliant on significant investment from national governments. Although several other geological storage sites are now in early stages of development, even in the unlikely event that they all proceeded, these are only likely to amount to around 30-40 Mt/year of capacity by 2030.[11] Given that on the order of 100s of Mt of CO_2 will need to be captured and sequestered annually in the EU by 2050, the current decade will be a critical period for scaling up CCUS and creating the long-lasting policy and funding frameworks required to ensure deployment continues beyond the demonstration phase.

Furthermore, with complete phase out of free allowances under the ETS currently proposed for 2035, industrial emitters already face significant exposure to high carbon prices in 2030. Without ready access to deep decarbonisation technologies such as CCUS, carbon intensive industries across the EU will be left without a viable option to act on the price signal from the ETS, other than to leave the region. The only consequence of the ETS reform, in conjunction with the carbon border adjustment mechanism (CBAM), will be to increase the cost of these products for EU citizens and industry (due to the need to pay ETS allowances) without any climate benefit.

For technology-based CO_2 removals, the Commission's Communication on Sustainable Carbon Cycles currently proposes a (non-binding) EU-wide target of only 5 Mt of CO_2 to be stored in 2030 which is far below the levels required according to energy system modelling (at least 200 Mt/year at net zero).

In Europe, CCUS must be a truly international endeavour, in which Member States can share their CO_2 storage resources, develop new inter-regional infrastructure, and align their regulatory approaches and technical standards where necessary. CCUS is therefore in need of a comprehensive EU strategy that can address these challenges, outline the likely timeline and scope of deployment, catalyse funding and support, and provide clear

[11] Carbon Limits (2022) *The gap between carbon storage development and capture demand*. Clean Air Task Force (Jan 2022)

targets and optimised infrastructure planning. The political commitment signalled by this strategy would in itself create a more favourable environment for project investment, promoting a positive feedback effect on costs through derisking of project finance and learning-by-doing. Similar commitments and deployment targets for renewable energy – and more recently, hydrogen – in the EU's decarbonisation strategy have helped build industry and investor confidence in these sectors, driving deployment and rapidly bringing technologies down the cost curve.

The key aims of an EU CCUS strategy would include:

- Clear communication of the role and scope for CCUS in achieving Europe's climate goals – providing confidence to project developers and investors, raising awareness of the need for CCUS among other stakeholders and ensuring civil society can provide input.
- Coordinating Member State commitments and ensuring their plans for CCUS deployment can be realised through greater cooperation.
- Planning and coordinating the development of optimised transport and storage infrastructure
- Providing funding and regulatory drivers for CCUS deployment in a near-term (technology commercialization) and long-term (market-driven) phase
- Ensuring the needs of CCUS are comprehensively considered in forthcoming legislation and revisions of existing legislation

Communicating the role of carbon capture and storage in European climate policy

As outlined, CCUS is necessary to reach the European climate goals and must therefore be recognized for this role in European climate policy. It is important for the EU to clearly state that carbon capture and storage is not an expression of diminished climate ambitions or a delay in the transition from fossil fuels, but offers a faster, more resilient pathway to climate neutrality, particularly through its ability to mitigate CO_2 emissions from 'hard-to-abate' process industries and provide permanent removal of atmospheric CO_2. By taking a leading role in communicating the role for CCUS in decarbonising Europe, supported by the scientific evidence, the EU can help both Member State governments and CCUS project developers build awareness and support among stakeholders, that is ultimately essential for the technology to progress. New deployment policies should also be rooted in an open dialogue with civil society, labour unions, industry, and other stakeholders. In order to build trust and support, it is essential that new financial support mechanisms and legislation should promote the development of CCUS as a climate solution, rather than as a means to unnecessarily continue or increase the use of fossil fuels, or a reduction in efforts to support energy-efficiency, renewable energy, or other sustainable low-carbon technologies.

The EU should take steps to:

- Provide unambiguous, evidence-based messaging on the role of carbon capture and storage in reaching net zero and establishing low-carbon industries and jobs

- Support policy development and announcements which encourage the development of carbon capture and storage with the sole aim of reaching European climate goals.

- Actively engage on CCUS with a broad range of relevant stakeholders and encourage Member States to do the same
- Establish a permanent stakeholder network/forum, including a working group of MS representatives
- Develop an online portal as a public information service, highlighting the need for the technology in reaching net zero and showcasing key projects and developments

An EU-wide policy framework for CCUS deployment

Depending on local factors such as geology, availability of clean energy, sources of emissions and political constraints, not all Member States may choose to store CO_2 within their jurisdictions, or to include carbon capture and storage as part of their climate strategies. For Member States who see little to no role for carbon capture and storage in their National Energy and Climate Plans, the EU should ensure that sufficient realistic and deliverable alternatives are included.

For Member States who do intend to rely on carbon capture and storage to achieve their climate targets, the EU can help ensure that these technologies constitute a viable, equitable, and open-access solution for all regions and industries that require them to decarbonise. The EU can help keep those Member States on track to meet their own deployment ambitions for CCUS, based on projections of likely capture volumes and potential storage sites. This would ensure that any emerging shortages in domestic storage or product-based sinks are apparent, and that planned CO_2 export volumes are visible to potential recipient Member States, allowing both parties to plan infrastructure accordingly.

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

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

- Set clear milestone targets (2030, 2040, 2050) for deployment of industrial capture and technology-based CO_2 removals based on scientifically sound long-term modelling and a climate risk minimization approach. Such targets could be expressed as Mt of CO_2 stored, a number of CO_2 capture projects deployed in key sectors, developed storage capacity, or the creation of low-carbon industrial clusters.
- Require Member States to formally and clearly declare the planned role of CCUS in their NECPs and long-term climate strategies, identifying the corresponding requirement for domestic storage development or CO_2 export to other states.
- Establish a position on the appropriate manner of regulation for CO_2 storage to avoid monopoly power and ensure principles of open-access, while stimulating competition and expansion.

- Commit to tabling a comprehensive legislative framework for CCS infrastructure, similar to the approach that has been taken for hydrogen infrastructure.
- Review and consider additional long-term regulatory tools to ensure net zero is achieved, such as geological carbon accounting, the creation of tradable CO_2 storage units (CSUs), and producer responsibility
- Clarify the position of CCUS in relevant forthcoming EU legislation and ensure such legislation and funding is coordinated with Member State initiatives

A potential roadmap for CCUS in Europe

Technology commercialisation and cluster formation phase – 2025-2032

During this first phase of deployment, low-carbon clusters and associated CO_2 infrastructure should be initiated and developed in the majority of Europe's major industrial zones that have reasonable access to CO_2 storage or a suitable port. These developments will be linked with large-scale storage hubs that are currently beginning to be developed in the North Sea, as well as two to four new storage sites in Southern Europe and Central and Eastern Europe – potentially based around currently nascent developments in the Black Sea, the Adriatic Sea, and South-West France. By 2032, North Sea storage alone should have the capacity to inject 40-50 Mt of CO_2 annually. Clusters will use localised onshore pipeline networks, as well as road, rail, and inland waterways for accessing dispersed industrial emitters on their periphery, and CO_2 shipping terminals where necessary. This phase of development will be primarily based around industrial decarbonisation and capture technologies in key sectors, such as cement, 'grey' hydrogen, refinery crackers, and steel production, should be de-risked through deployment to a relatively standardised 'n^{th} of a kind' status. Technology and infrastructure deployment will initially rely on significant public funding through mechanisms such as the Innovation Fund, Connecting Europe Facility, and Member State initiatives. However, industrial exposure to the ETS price will increasingly drive projects with access to infrastructure and derisked capture technology.

Commercial phase and regional interconnectivity – 2032-2040

This phase will begin to see greater connectivity between industrial clusters, through national and international networks and greater use of long-distance 'trunk line' pipelines. Through these networks and other CO_2 transport modalities (particularly shipping), by 2040, all major industrial sources in Europe should have access to CO_2 storage. Carbon trunk lines will be established along key transport corridors, enabling economies of scale and connecting major industrial clusters with storage areas. Total storage capacity in the region should aim to reach at least 300 Mt/year, with roughly half of this likely to be in the North Sea. Industrial emitters are fully exposed to the carbon price (projected to be >150€/t) and demand-drivers for low-carbon products should increasingly provide a business case for industrial decarbonisation through CCUS or other means. In addition, the development of commercial-scale carbon removal projects from direct air capture, as well as use of biomass at point sources will also increase significantly over the decade, partly driven by the integration of CO_2 removal in the EU's 2040 emissions target. Permanent storage of atmospheric CO_2 should aim to reach on the order of 100 Mt by the end of this period.

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

In a final decade to reach carbon neutrality, as unabated fossil carbon emissions diminish there will be increased growth in technical CO_2 removals, including DAC and BECCS, which should aim to reach at least 200 Mt/year by 2050. This growth will primarily be driven by a market-based price signal for removals to be determined by EU policy. To accommodate growth from removals and remaining industrial and power sources, total annual storage capacity will be required to reach at least 500 Mt/year. During this period, a highly competitive, harmonised, and flexible regional market for CO_2 transport and storage should be established, in which emitters have access to a range of possible CO_2 storage sites or offtake for CO_2 utilisation.

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

Like most decarbonising technologies, implementing CCUS imposes a cost on emitting industries, including capital costs and ongoing operating costs for CO_2 capture, as well as the payment of fees to providers of CO_2 transport and storage. The ETS may ultimately provide an adequate investment signal for industrial emitters to internalize these costs, but manufacturing industries are currently shielded from the ETS by the free allowances that are allocated to ensure they remain internationally competitive. Moreover, even the record-setting ETS allowance prices of around €100/t seen in 2022 remain too low to drive the deployment of CCUS in many sectors, particularly for first-mover projects that also need to support infrastructure deployment or pay high fees associated with early, lower-volume infrastructure. Taking into account the carbon price and existing funding schemes, there is a revenue shortfall for currently announced projects which is estimated to amount to a cumulative €10 billion by 2030 (Figure 2).

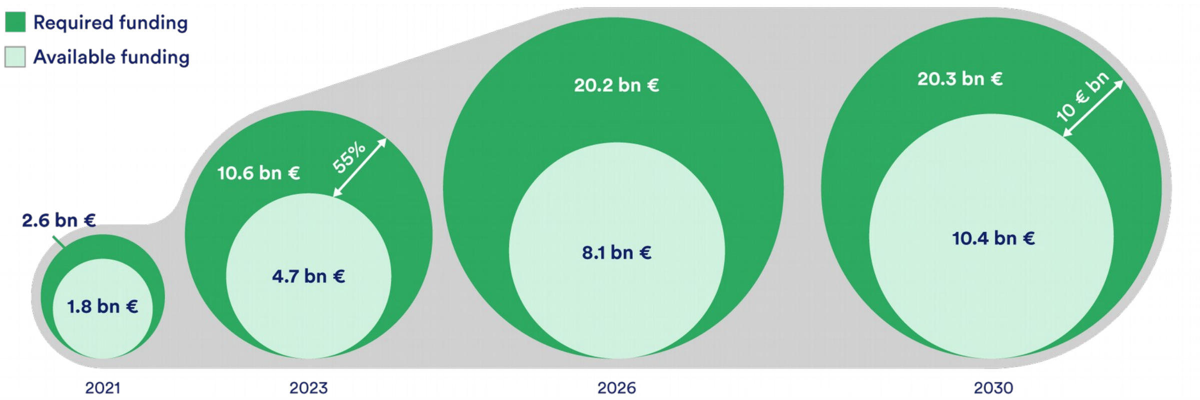


Figure 2. Estimates of the gap between announced funding for carbon capture and storage and the funding announced projects require to have a positive net present value (cumulative over time)[12]

In order to close the financial gap between current carbon prices and the cost of first-of-a-kind CCUS deployment in industry, several Member States have implemented or proposed a form of 'Contract for Difference' or related mechanisms, in which the State subsidises the difference between a carbon reference price (such as the ETS) and a 'strike price' representing the project's true costs per tonne of CO_2 abated. Operating on this principle, the Netherlands' SDE++ scheme for decarbonizing technologies has included CCUS and enabled the Porthos project (covering four emitters in the Port of Rotterdam) to progress towards a final investment decision in 2022. Similar mechanisms are proposed for funding CCUS and industrial decarbonisation in the UK, Denmark, and Germany, and may be included under the current revision of the Innovation Fund. This approach

[12] Carbon Limits (2022) The gap between carbon capture and storage ambitions and available funding. Clean Air Task Force (Jan 2022)

has the advantage of providing a predictable, annual revenue to projects over the contract period, while also allowing the total subsidy to decline over time as the carbon price increase. For non-industrial applications of CCUS, such as hydrogen production, power generation, and CO_2 removals, other forms of CfD-based subsidy may be necessary, for instance, based on strike and reference prices for hydrogen and power, or the market value of a removal credit.

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

- Increase the size and scope of the Innovation Fund or introduce alternative mechanims to cover projects that deliver significant decarbonisation through:
  - Significant optimization of high TRL technologies;
  - High impact application of a demonstrated technology in a new region or sector;
  - Innovation beyond technology – in development of commercial models or supply chains
- Encourage Member States to develop funding mechanisms which provide a bankable revenue stream over a project duration, for example, via a carbon contracts for difference model
- Ensure new and existing funds for industrial decarbonisation funds are accessible to carbon capture and storage
- Promote negative emissions via carbon capture and storage by developing a European certification system for CO_2-removal, which can eventually be linked with better incentives through the ETS

Establishing large-scale, open-access storage

The promising progress of nationally supported CO_2 transport and storage projects such as Norway's 'Northern Lights' and Denmark's recent announcements has catalysed the recent growth in plans for CO_2 capture projects, however, the development of geological storage sites is falling far behind demand. With a potential 50% shortfall in developed storage capacity projected by 2030, it is clear that the timely development of storage sites is a critical element in the deployment of CCS in Europe (Figure 3). Including the North Sea resources of the UK and Norway, Europe is estimated to possess on the order of hundreds of gigatonnes of theoretical capacity for CO_2 storage[13], but individual storage sites can take several years to develop, requiring detailed geological assessments and often lengthy permitting processes. Developments can also require significant pre-construction phase investments that carry a financial risk unless there is certainty of demand from CO_2 capture plants and,

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

despite the recent growth in industry interest, this demand remains uncertain while so few Member States have committed significant political backing or funding to CCUS.

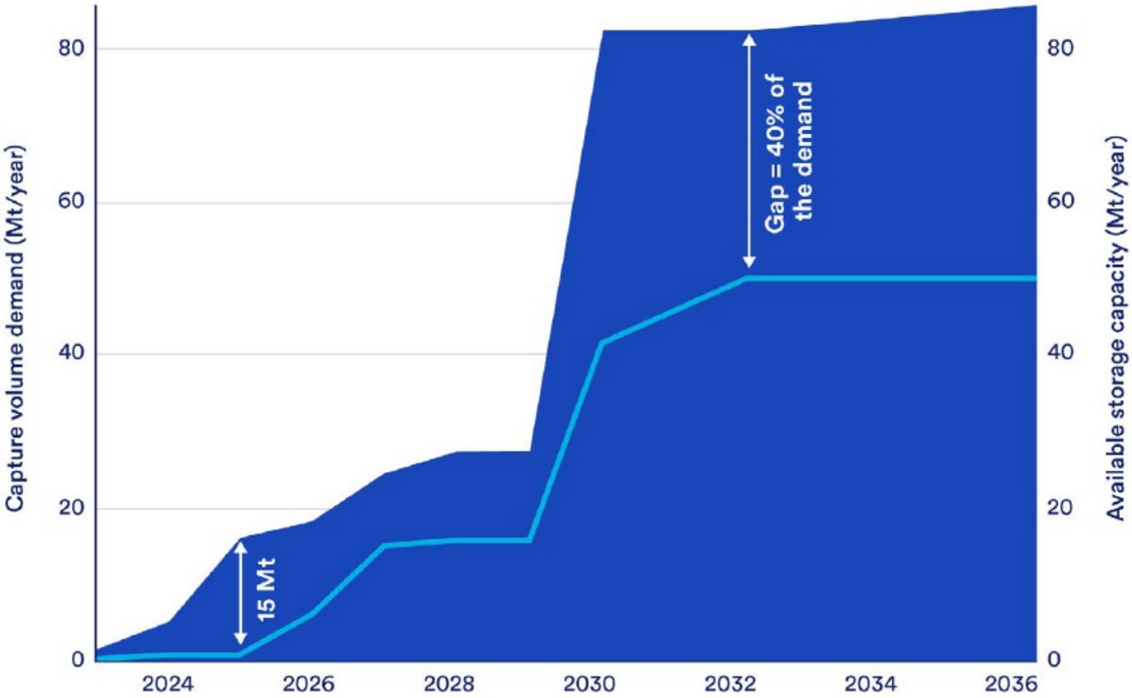
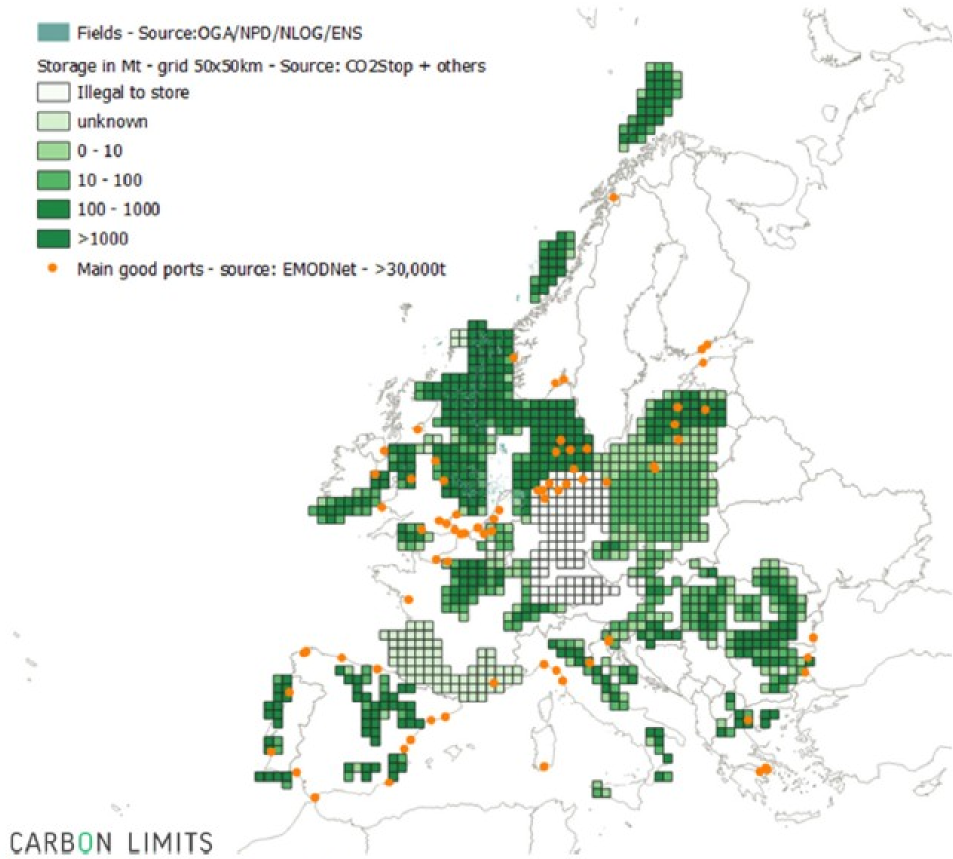


Figure 3. The widening gap between volumes of CO_2 captured and available storage sites[14]

[14] Carbon Limits (2022) The gap between carbon storage development and capture demand. Clean Air Task Force (Jan 2022)



Source: Carbon Limits analysis

Figure 4. Regional CO_2 storage capacity in Europe based on current estimates[15]

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

- Develop a plan to identify and develop strategically placed storage sites, based on Member State submissions of prospective capture and storage volumes
- Provide funding for relevant expert bodies (e.g., geological surveys) to establish an open-access CO_2 storage resource 'atlas' for the whole region
- Provide dedicated funding to characterize and mature large-scale (>100 $MtCO_2$) storage sites in strategic locations to 'injection-ready' status – this could potentially include a tender process to reach target storage capacities by key dates.

[15] Carbon Limits (2021) Re-Stream. Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe.

- Ensure that EU or MS-funded projects with a CO_2 storage component include surplus, open-access capacity
- Introduce regulatory requirements for the oil and gas industry to undertake steps towards storage site development, including the acquisition and sharing of data and a requirement to investigate the storage potential of reservoirs nearing depletion (or allow others to do so)
- Incentivise industry to reuse existing oil and gas infrastructure for CO_2 and prevent decommissioning of infrastructure likely to be required in future
- Provide EU guidelines to streamline storage site permitting (aiming for a maximum of 9 months) and create a platform for knowledge sharing and capacity building between the relevant Member State regulators
- Investigate new approaches to the financial security requirement for storage sites (such as a portfolio approach) and the creation of an EU-wide insurance fund
- 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

It is also important to acknowledge that current plans for CO_2 storage development are heavily concentrated in the North Sea, where well-characterised, favourable geology, existing offshore assets, and supportive policy provide a commercial opportunity. However, suitable storage geology is found in most regions of Europe (Figure 4), including well-located onshore storage resources in Central and Eastern Europe and offshore storage in the Mediterranean. These areas must also be developed to viable sites to ensure that all the EU's emitting industries are able to access decarbonizing infrastructure, but many countries face challenges including inadequate or limited implementation of the CCS Directive, a shortage of regulatory or technical capacity, and increased communication challenges associated with onshore storage. Development of CO_2 storage in new regions should be accelerated through sharing of technical and regulatory best practice, capacity building within Member State governments, and EU-coordinated efforts to identify and develop promising storage sites:

- Promote capacity building initiatives for government and other stakeholders in relevant Member States, particularly in relation to storage site permitting requirements
- EU-coordinated efforts to update CO_2 transport and storage regulations in Member States, such as the CCS Directive, Gas Directive and Gas Regulation.
- Explore ways in which the Just Transition Fund could be used more broadly to help industrialised regions to access CO_2 storage

CO_2 infrastructure for Europe

Creating clusters and localised infrastructure

Most of Europe's current wave of carbon capture projects are based on the premise that the commercial framework for CO_2 capture can be separate from that of transport and storage. Under this model, an emitter would pay to install and operate the CO_2 capture process, and then provide a CO_2 transport or 'transport and storage' entity with a fee to take CO_2 at the plant fence. It is unrealistic to expect that an industrial emitter will be willing, or indeed able, to undertake investments in CO_2 transport and storage, where it has no expertise. In addition to simplifying project structure for emitters, this approach lends itself to the development of shared infrastructure that can achieve economies of scale by processing large volumes of CO_2, while also providing a solution even for small emitters that may not justify new CO_2 infrastructure alone. Heavily industrialised zones or ‘clusters’, often associated with port areas, are the most promising first-movers for establishing this kind of shared CO_2 network, potentially alongside complementary infrastructure for hydrogen and heat (Figure 5). A CO_2 network in the Port of Rotterdam (linked to offshore storage) is proposed by the Porthos project, while the Innovation Fund-selected Kairos@C project envisages a similar solution for emitters in Antwerp. In Copenhagen, a network of local waste-to-energy, combined heat and power plants, and other emitters, are planning shared infrastructure under the ‘C4’ project.

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

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

Figure 5. Illustrative schematic of a decarbonised industrial cluster in the Port of Dunkirk, including a CO_2 network, export terminal, and connection to inland emitters through non-pipeline transport.

Inter-regional and international transport networks

Cross-border transport of CO_2 will be integral to even the earliest stages of CCUS deployment in Europe and will extend beyond the borders of the EU (Figure 6). Several of the most progressed capture and storage projects are based on shipping of CO_2 to collection points associated with offshore storage in the North Sea (or to basalt storage in Iceland). Many planned industrial clusters without direct access to storage within the Member State, such as those at Dunkirk and Antwerp, will rely on shipping in the first instance, potentially progressing to pipelines in the long-term. A pipeline connection to connect North Sea storage to the heavily industrialised area of North-Rhine Westphalia is also proposed. In the longer term (2032 onwards), wider regional CO_2 networks will be required, giving access to more dispersed emitters and inland clusters further from storage, and forming connections between clusters. In addition to expanding access, larger networks will help reduce costs through economies of scale and project risk by providing CO_2 emitters and offtakers with a wider portfolio of sinks and sources.

The EU can help guide and derisk the development of an inter-regional CO_2 transport network by identifying the key transport routes and potential trunklines, including potential volumes to be transported. It is also vital to ensure that CO_2 networks in each Member State develop in a coordinated and harmonised manner, with shared technical standards for CO_2 specifications and compatible regulatory protocols. Long-term planning of a pan-

European CO_2 network will also help early-stage transport options progress towards cost-optimum solutions (such as shared pipelines or large-scale shipping where appropriate), and avoid lock-in of higher cost configurations.

- Develop an overarching plan for the development of optimized cross-border CO_2 transport infrastructure, including a 'CO_2 backbone' pipeline for Europe and solutions for dispersed emitters
- Plan the development of an initial 'no regrets' infrastructure
- Establish a 10-year Network Development Plan for CO_2 infrastructure, following the model of gas and electricity networks
- Develop a Europe-wide set of CO_2 specification standards for transportation and storage
- Establish a platform for coordination between transport network operators
- Encourage or require Member States to ratify the amendment to the London Protocol concerning cross-border transport of CO_2 and establish guidelines for bilateral arrangements or agreements on cross-border transport
- Establish a Europe-wide regulatory platform for CO_2 transport infrastructure, ensuring open-access principles
- Provide guidelines on how to collaborate and trade CO_2 with non-EU countries, and include recognition of CO_2 storage in the UK as non-emitted CO_2 under the EU ETS

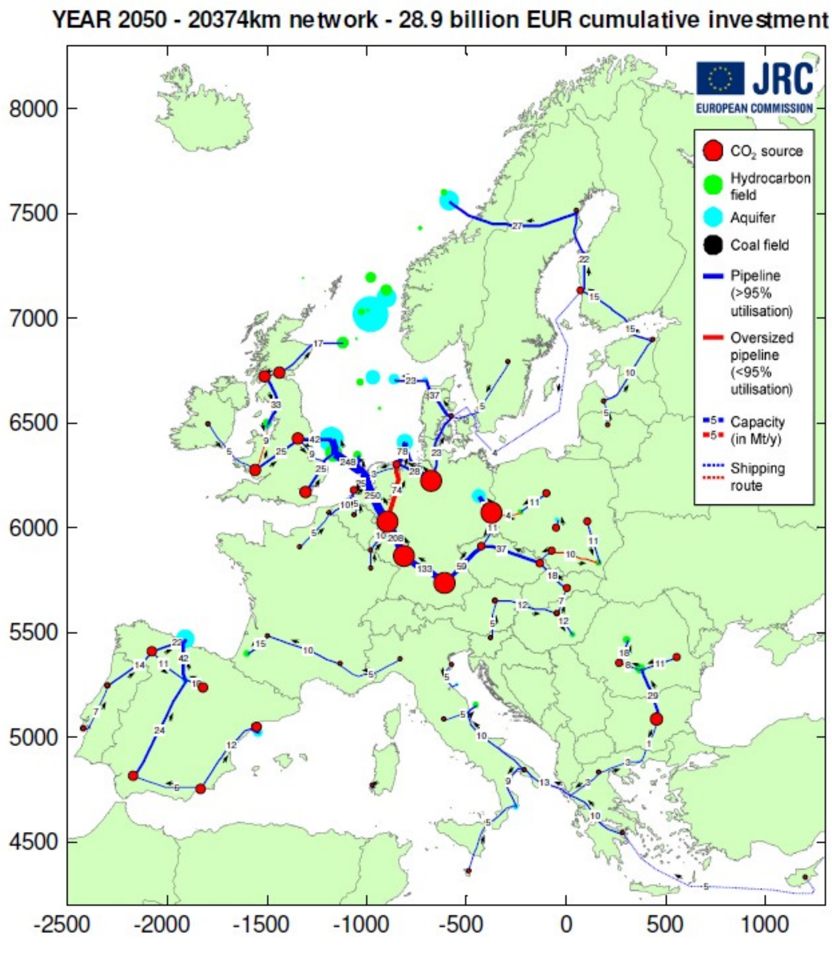


Figure 6. A potential trans-European network for CO_2 (*requires updating*)[16]

Sectoral applications of CCUS and discussion of long-term incentives

CCUS for permanent carbon dioxide removals

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

1. further reducing net emissions in the near-term

2. counterbalancing residual emissions to help reach net zero emissions in the mid-term

3. achieving and sustaining net-negative emissions in the long-term.

The geological storage of atmospheric CO_2 obtained either through direct air capture or processing of climate-beneficial biomass are carbon removal solutions that offer accurately measurable and permanent storage of CO_2 with very low risk of reversal. There is an important role for governments, including the EU and its Member States, to establish rigorous certification mechanisms and introducing funding streams for higher-cost, high-value forms of real, measurable, permanent carbon removal, without compromising efforts to reduce emissions by:

- Developing a portfolio of removal options for Europe, emphasizing that carbon removal must be real, permanent and measureable.
- Ensuring the forthcoming EU certification mechanism for carbon removal is based on a full life-cycle analyses, ensures additionality and minimises uncertainties around monitoring, reporting, verification, permanence and leakage
- Targeted funding mechanisms to support the early development of real, measurable, permanent carbon removals.
- Set scientifically informed targets for carbon removals
- Set standards to encourage the use of waste biomass feedstocks and limit new land clearing

Furthermore, the importance of establishing a European network to transport and permanently store CO_2 will be an important enabler for the development of carbon removals in the future.

CCUS for industrial processes

The EU's manufacturing industries are a key component of the wider economy, providing the critical materials – such as cement, steel, chemicals, plastics and others – that will remain essential to our way of life for decades to come. As the EU transitions to a carbon neutral future, there will be new and growing demands on many of these materials, for applications such as wind turbines, photovoltaics, high-voltage transmission lines, electrified transport, and energy efficient buildings. However, these industries are also highly energy and emissions intensive, accounting for up to a quarter of total EU emissions (including energy-related emissions). While many processes may be decarbonised via electrification, achieving net zero will mean also tackling 'hard-to-

[16] Morbee J, Serpa J, Tzimas E (2010) The evolution of the extent and the investment requirements ofa trans-European CO2 transport network. JRC (2010)

abate' emissions such as the process emissions from cement, lime, and chemicals, and emissions from remaining use of fossil fuels (or biomass) for driving high-temperature processes. The EU is in a position to lead the world in demonstrating that truly zero-carbon industries are achievable, while ensuring that the thousands of direct and indirect jobs associated with these industries remain within the EU. CCUS is expected to play a critical role in fully decarbonising heavy industries and is currently the lowest cost or the only option for several sectors (Figure 7). As other countries, including the US, Canada, and the UK, accelerate the development of CCS for low-carbon industry, there is growing urgency for the EU to ensure its industries can also remain competitive and viable in a low-carbon future.

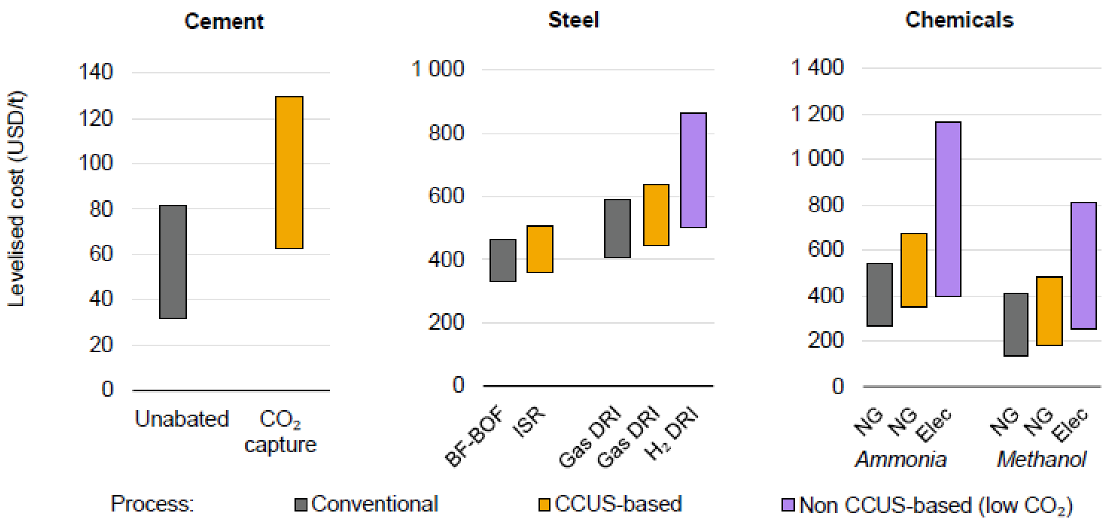


Figure 7. Estimates of levelized cost of producing low-carbon cement, iron and steel, and chemicals via different production routes[17]

[17] IEA (2020) Special report on carbon capture utilisation and storage. CCUS in clean energy transitions. Paris, France, International Energy Agency, 174 pp (Sep 2020)

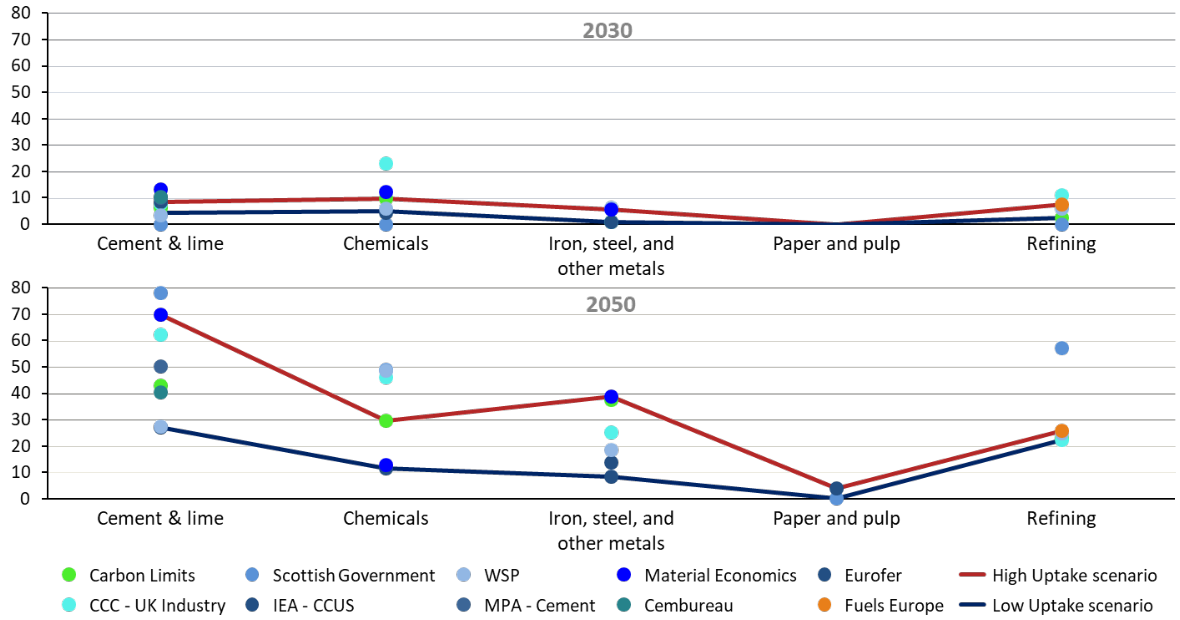


Figure 8. A review of projected CCUS deployment in key industrial sectors in 2030 and 2050, based on various literature sources[18]

Many of these sectors are yet to see adoption of CCUS for a full-scale plant anywhere in the world. However, supported by initiatives such as the Innovation Fund, several processes may be first pioneered in the EU. As for most applications of CCUS, it will be necessary to create a policy-backed commercial case for early projects – beyond a first-of-a-kind plant in each sector – during a transition period to 2035, when industry will be fully exposed to the carbon price. This will ensure that the technologies and infrastructure required for widespread commercial deployment are available and cost-optimised in time. From 2030, decarbonised industry should begin to move from a reliance on government support towards decarbonisation driven by market 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 much less significant, and therefore easier for consumers to absorb, when applied to end-use products such as cars or buildings.[19] EU policy can help accelerate this transition by developing low-carbon product certification, setting regulatory standards for end-user products, and seeding initial demand through public procurement initiatives. Many of these measures can build on existing or forthcoming legislative packages such as the Sustainable Products Initiative and could include:

- Developing rigorous low-carbon product certification
- Implementing public procurement of low-carbon products such as concrete and steel
- Introducing carbon intensity limits for end-use sectors such as construction and vehicles
- Setting sectoral targets for the adoption of low-carbon products

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

[18] Element Energy (2022) European CCS potential and economic impacts. Element Energy, Cambridge, UK (Apr 2022)

[19] Rootzen J M, Johnsson F (2016) Paying the full price of steel – perspectives on the cost of reducing carbon dioxide emissions from the steel industry, *Energy Policy*; 98; 459-469 (2016), and Rootzen J M, Johnsson F (2016) Managing the costs of CO2 abatement in the cement industry, *Climate Policy*; 17 (6); 781-800 (Jul 2016)

CCUS in the power sector (placeholder)

Will outline the potential role for CCS in decarbonising existing generating assets and providing grid flexibility and resilience through CCS-equipped thermal power plants. The potential for negative emissions through CCS-equipped biomass-fired power plants, and the role of this pathway for repurposing coal-fired assets.

Conclusions

There is growing scientific and political consensus that the widespread deployment of CCUS (on the order of 100s of Mt/year) will be required if the EU is to achieve its climate goals. As this need becomes apparent through long-term analysis of viable decarbonisation pathways on a national level, several Member States – particularly in the North Sea region – have begun to actively support and deploy the technology. Now, there is an important role for the EU to play in coordinating, optimising, and accelerating these developments – which will necessarily take place on a cross-border basis – while also ensuring that no MS or region is left behind in their efforts to decarbonise using CCUS technologies. To this end, this Vision document provides a first step and set of recommendations towards a comprehensive CCUS Strategy for the EU

Appendices

Industry case studies

Cement and lime

The cement and lime industry is one of the EU's most greenhouse gas-intensive industrial sectors, accounting for over 3% of the region's greenhouse gas emissions[20]. As around two thirds of the CO_2 released by cement and lime plants are associated with the calcination of calcium carbonate, these 'process emissions' are impossible to avoid through fuel switching or electrification and can only be addressed with CCUS. The cement industry therefore features heavily in current plans to deploy CCUS at scale in the region, with one project currently under construction at Brevik in Norway, and a further four projects selected under the first two calls of the Innovation Fund in France, Bulgaria, Germany, and Poland (in addition to a lime plant in France). Other strategies for cement and lime decarbonisation include improving process efficiencies (generally already maximised at EU sites), switching to low-carbon fuels or electricity for process heating, and in the case of cement, using clinker substitutes such as fly ash. However, most industry projections foresee a role for CCUS in up to around half of the CO_2 abatement required to reach net zero. In the long-term, lower-carbon alternatives to cement – such as magnesium oxide-based materials – may become technically mature, but these are not anticipated to make a significant contribution within the timeframe of net zero by 2050.

There are several technical approaches being developed to capture CO_2 from cement and lime plants: First, post-combustion treatment of standard flue gases using CO_2 capture solvents – as employed at Brevik. Second, an oxyfuel process, as proposed under the K6 project in France and at Lägerdorf in Germany, in which combustion

[20] Impact assessment accompanying the document 'Stepping up Europe's 2030 climate ambition'. European Commission (17 Sep 2020)

and calcination is carried out in a mixture of oxygen and CO_2, producing a relatively pure CO_2 stream. Third, the cement kiln can be indirectly heated, thereby separating CO_2-rich process emissions from combustion-related emissions, as currently trialled at the pilot scale under the 'LEILAC' project in Belgium (and its planned scale-up in Germany); this process could be most effectively combined with indirect heating through electrification or another low-carbon heat source. Each of these technologies merits further development, as the optimum solution for a given plant will depend on a number of site specific factors, including availability of waste heat, low-carbon fuels or electricity, and oxygen (potentially as electrolyser by-product).

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

Once the capture technologies are fully commercialised and CO_2 infrastructure widely available, the production of low or zero-carbon cement can be most effectively incentivised through market demand in the buildings sector. This could begin with procurement of low-carbon cement for public projects, and extend to the private sector through regulatory measures such as the incorporation of carbon footprints in buildings standards. Concrete production also offers high potential for the permanent sequestration of CO_2 through mineralisation, for which new CO_2 accounting methodologies should be established.

Steel

The iron and steel sector is the largest source of industrial emissions in the EU, accounting for over 5% of total greenhouse gas emissions.[21] Steel is an iron alloy that can be made through two main routes: 'primary steel' from the processing of iron ore, and 'secondary steel' from the recycling of scrap steel in an electric arc furnace (EAF). Secondary steel is much less carbon-intensive than primary steel, and currently accounts for around 40% of European production, but there are limits to how much steel can be recycled, based both on suitable scrap availability and quality requirements of the end product. A significant proportion of primary steel production will therefore continue to be required in future.

Nearly all the EU's primary steel is produced via the highly carbon-intensive blast furnace route, in which iron ore is chemically reduced with coking coal at high temperatures, before further processing to steel in a basic oxygen furnace. Many of the region's steel producers are now pursuing a shift towards the alternative direct reduced iron (DRI) process, which can be fuelled by natural gas (roughly half as carbon intensive as the blast furnace route) or even entirely on low-carbon or renewable hydrogen – potentially cutting CO_2 emissions to much lower levels. Currently, the DRI process (mostly using natural gas) represents only around 5% of global steel production, and only one plant is operating in the EU. The principal challenge in transitioning all blast furnace sites to a low-carbon form of DRI is in sourcing sufficient volumes of hydrogen; studies indicate that over 60 billion m3 of hydrogen would be needed to match the 92 Mt of EU steel production in 2018. If derived

[21] Ibid

entirely from renewable-powered electrolysis, this would require nearly 350 TWh of renewable generation, or more than double total solar power output in the EU today.[22]

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

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

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

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

Waste-to-energy

Waste-to-energy (WtE) plants use heat derived from the combustion of municipal waste streams to generate power or directly supply heat for applications such as district heating. There are over 400 such plants operating across the EU, primarily acting as an alternative form of waste disposal to landfill (which is associated with climate harmful methane emissions), while also contributing to local energy generation. Although WtE plants represent a relatively small proportion of the EU's greenhouse gas emissions, many plants have already made plans to install CO_2 capture, often driven by ambitious municipal decarbonisation targets and the fact that no alternative decarbonisation options available. Waste recycling rates have steadily improved in the EU, but a proportion of non-recyclable waste is expected to remain, with CCUS-equipped WtE plants offering a low-carbon disposal route.

ARC's Amager Bakke WtE plant in Copenhagen has trialled a CO_2 capture technology and has proposed a full-scale system that would be an anchor project withing the planned 'C4' cluster – a collection of public utilities in the municipality exploring shared CO_2 infrastructure. A commercial CO_2 capture system is also operational at

[22] Conde A S et al. Decarbonization of the steel industry. A techno-economic analysis. Materiau et Techniques, 109, 305 (2021)

AVR's plant in Duiven, Netherlands, where 60 kt/year of CO2 is supplied to local greenhouses. Among the EU's immediate neighbours, WtE plants comprise nearly 40% of applications to the UK CCUS funding process, while in Norway, Oslo's Klemetsrud plant has received funding from the municipality and other investors.

Aside from local decarbonisation targets, there is currently little incentive to capture CO_2 from WtE plants, which remain outside of the ETS except for in Denmark and Sweden. However, the current revision of the ETS Directive may see WtE emissions of fossil origin subject to the carbon price. While this step can help drive decarbonisation of the sector, policy should be carefully designed to avoid diverting waste to landfill or export from the EU and, above all, ensure that recycling rates continue to be maximised. As for other industries, providers of low-greenhouse gas waste treatment will require new incentives to cover the cost gap with conventional disposal and ensure they remain competitive. This could potentially be through a contract for difference model until there is sufficient market demand for CO2-neutral waste handling services.

Given that around two thirds of incinerated waste streams are of biogenic origin, there is also a potential role for WtE plants in providing CO_2 removal through BECCS. On the other hand, EU policy under the Waste Directive currently aims to significantly reduce mixed bio-waste streams through separate collection, composting and anaerobic digestion. Going forward, the future role of CCUS in the waste sector should be properly integrated into the EU's overarching strategies for waste and carbon removals certification.

Chemicals - placeholder

Country case studies

- [PLACEHOLDER, introduction to the chapter, purpose to show, inspire etc., experiences from frontrunner countries]

Candidate case studies: Denmark, Netherlands, Croatia, Poland