# CCUS Policies and Business Models

## Building a commercial market

International Energy Agency

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# Abstract

Carbon capture, utilisation and storage (CCUS) is an important technology for achieving global net zero emissions. Momentum on CCUS has increased in recent years, but the deployment of projects has remained relatively flat. Emerging business models are opening the door to new investment opportunities, and with that bringing new challenges to be overcome.

The scale-up needed to reach net zero emissions by mid-century represents a major undertaking, and policy support and co-ordination are crucial. Policy makers have a suite of tools at their disposal to create the conditions necessary to drive long-term investment, enabling industry to take the next step forward and push CCUS into a viable and sustainable commercial market.

This IEA CCUS Handbook provides governments with a policy toolkit to tackle the overarching challenges to CCUS deployment. It gives an overview of existing policies that have helped launch CCUS projects to date and identifies the main challenges to future large-scale deployment. The handbook also highlights international best practices, drawing on existing and proposed government efforts to address these challenges.

The handbook is supported by our CCUS Projects Database[1] and complements the IEA CCUS Handbooks on Legal and Regulatory Frameworks for CCUS and on $CO_2$ Storage Resources and their Development.

[1] The IEA CCUS Projects Database available for download contains projects updates as of February 2023. This report relies on an internal version of the database with project updates as of Q2 2023, with the exception of major project updates, which include projects (re)entering operation or construction, which are included up to October 2023.

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# Executive summary

## Carbon capture, utilisation and storage (CCUS) is an important tool for emissions reduction and removal

**CCUS accounts for 8% of cumulative emissions reduction in the Net Zero Emissions by 2050 Scenario (NZE Scenario) to 2050**. CCUS is particularly well suited to applications characterised by highly concentrated $CO_2$ streams and those lacking technically or commercially available solutions for carbon abatement. Moreover, it is the only technology-based solution for carbon removal, where $CO_2$ is captured directly or indirectly from the air and permanently stored underground. Carbon removal can help balance residual emissions from heavy industries and long-distance transport.

**Governments have taken different approaches to supporting CCUS projects, either through broad funding incentives or targeted support for selected projects**. Two types of policies in particular have contributed to the CCUS projects in operation today: legal and regulatory frameworks that facilitate and enable deployment, and cost reduction measures, such as grants, tax credits and the use of state-owned enterprises (SOEs). These measures combined have supported early large-scale projects to move into operation.

## New business models are emerging, shifting risk allocation across the value chain

**The full-chain business model has played an important role in the early development phase of CCUS.** In such models, a single project framework is used for the full CCUS value chain from $CO_2$ capture to transport and storage. The oil and gas industry has played a major role in these projects, thanks to its expertise in operating large-scale projects and knowledge of the subsurface. However, the industry's historical focus has been enhanced oil recovery (EOR) and a shift is now required to one that centres on dedicated $CO_2$ storage.

**While the full-chain business model has some advantages, it comes with multiple risks at each step of the chain.** These are typically associated with a need for technical and operational expertise in all fields, and high CAPEX. Full-chain business models alone are not well suited to CCUS applications needed for net zero, as some emitters may not have the internal expertise. For capture, this is particularly relevant for applications where $CO_2$ is not already separated as part of the process, and which require dedicated capture equipment.

**New part-chain business models are emerging, characterised by separate entities specialising in different parts of the CCUS value chain**. While the oil and gas sector continues to play a role, new specialised players are entering the market, such as chemical and engineering companies to provide $CO_2$ capture solutions and infrastructure, shipping companies that are expanding their portfolio, and new companies focusing exclusively on CCUS. Old and new players are now establishing joint ventures in a CCUS hub configuration, which today appears to present a promising opportunity. CCUS hubs can shorten lead times for connecting to shared infrastructure, reduce costs through increased competition within a more specialised corporate landscape and through cost-sharing on infrastructure, and allow more dispersed and smaller emitters to connect to $CO_2$ transport and storage (due to economies of scale).

**With new business models come new project complexities.** These include greater need for co-ordination across the value chain, mitigation of counter-party risks, allocation of long-term liability, and management of shared, cross-border $CO_2$ transport and storage infrastructure. Governments can support the deployment of these new models and step in where challenges remain and the private sector struggles to progress.

## Global project announcements are growing exponentially, but challenges for deployment remain

**CCUS deployment has remained relatively flat in the last decade, partially due to a lack of policies to support the establishment of a sustainable market for CCUS**. This lack of progress has led to progressive downward revisions in the role of CCUS in the IEA's updated NZE Scenario. Momentum, however, is growing. Over the past 3 years, more than 400 new projects have been announced along the CCUS value chain, and over 45 countries have CCUS projects in development. While the current project pipeline would only meet just over one-third of deployment needed by 2030 in the NZE Scenario, these needs could be met in full if momentum continues, projects reach commissioning on time, and lead times are reduced. The call is on industry to successfully deliver on CCUS projects, and for policymakers to support them.

**There is a need for continuous innovation to reduce energy penalty and costs for CCUS applications**. While some CCUS technologies have been in use for decades, operating CCUS projects have been largely concentrated in lowest-cost areas such as natural gas processing. In contrast, around three-quarters of capture capacity by 2050 in the NZE Scenario relies on technologies and applications that are still at demonstration or prototype scale. For all CCUS applications, economic viability remains a significant hurdle, as costs can be prohibitively high compared to unabated technologies. In addition, long lead times for project development and implementation can further impede progress, particularly related to $CO_2$ storage development.

## A suite of policy tools is needed

**Countries are recognising the value of CCUS in meeting their climate and energy goals, but there is a gap between intention and action**. Around half of the countries with a net zero pledge in place (48 out of 93 countries plus the European Union) have identified CCUS as contributing in some way to the target. Despite this, under 20 countries have CCUS policies on the books that go beyond R&D initiatives. Grants and tax credits, and an enabling legal and regulatory framework alone are insufficient to scale up CCUS across applications at the required pace. The creation of a commercial market for CCUS requires a suite of policy tools to address all the challenges associated with CCUS deployment, and ensure that investment continues to flow into CCUS projects, and projects are completed on time.

**Particular attention must be placed on supporting CCUS deployment in emerging markets and developing economies (EMDEs).** Approximately half of all $CO_2$ capture capacity in the NZE Scenario is located in EMDEs by 2030, up from one-third today. Following the closure of the Asian Development Bank's CCS Trust Fund in 2022, and with the planned closure of the World Bank's CCS Trust Fund in 2024, there will be a major gap in multilateral development funding support for CCUS in EMDEs. Dedicated international funding instruments are needed to support the development of CCUS-enabling environments and/or piloting, as most EMDEs typically rely on some level of multilateral development funding to perform the technical assistance studies that underpin the development of legal and regulatory frameworks and CCUS policies.

**The IEA has developed a policy toolkit for governments to build a commercial market for CCUS and tackle the overarching economic, lead time, innovation and complexity challenges to deployment**. How governments approach this will depend on institutional, economic and political factors that will influence whether they opt for more or less intervention, or shift their approach as the market develops. These tools will help to create an enabling environment for CCUS, and can help reduce costs to spur early market movement, support revenue streams to secure necessary infrastructure, set strategic targets to signal long-term commitment and regulate industrial activities to drive market demand.

## A policy toolkit for CCUS

### Policy approaches for CCUS deployment

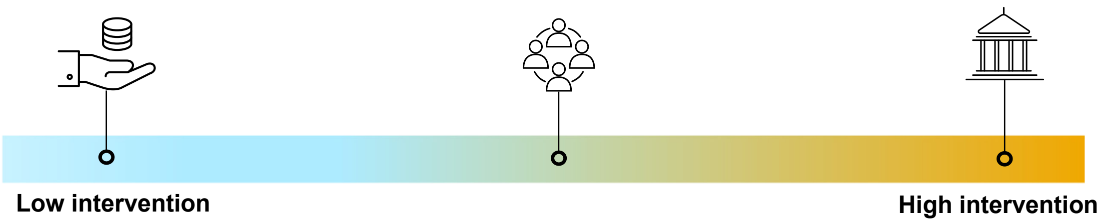
There is no one single approach to building a commercial market for CCUS. Various approaches should be thought of as existing on a spectrum: **incentive- or penalty-based**, **shared cost allocation** and **full control** approach.

Institutional, economic and political factors will influence what part of the CCUS policy spectrum a country may end up on, and countries may move along the spectrum as these factors change and as the domestic market for CCUS matures. Where a country sits on the spectrum may impact the types of policy tools that it chooses to use.

**Approaches**

| Incentive- or penalty-based approach | Shared cost allocation approach | Full control approach |
|---|---|---|
| Policies to influence how a private company will make its investment decisions. This is either done with **incentives** (e.g. grants, loans or tax credits) to private companies to deploy a certain technology or adopt a certain practice, or with **penalties** (e.g. taxes or fees) for not complying with regulations. | Economic parameters govern the cost and revenue structures of a company, which is shared between the public and private sectors. This approach may be well suited for large infrastructure endeavours, such as the development of a $CO_2$ transportation and storage network. | Instead of solely relying on the private sector to develop a market, this approach leans on state-owned enterprises to finance, build, own and operate projects. It may still rely on some level of private sector involvement, whether it is through jointly developing projects, as a customer or as an investor. |

**Level of government intervention**




### Policy toolkit to address CCUS challenges

Governments have several policy tools to address challenges to CCUS deployment. It is important that these tools work together to tackle **economic viability**, **lead time**, **innovation** and **complexity** challenges.

Whatever tools a government chooses to employ will be unique to that country, but it is vital that the tools are effective and efficient, setting up a viable and sustainable commercial market for CCUS that attracts investment and retains it over the long term.

**Challenges**

| Economic viability | Lead times | Innovation gaps | Project complexity |
|---|---|---|---|
| Absent any policy support, the economic viability of a CCUS project is a major barrier to wide-scale deployment. High costs and a lack of revenue streams for projects directly impact a project's economic viability. | Lead times (i.e. the total time required between a project's conception and commissioning) currently average around six years. Reaching net zero goals hinges on cutting these lead times. | The technology maturity of CCUS varies considerably by technology type and application. Technologies which are mature today are also not necessarily the ones consistent with a net zero energy system. | The shift to a hub model means a complex project structure, with implications for risk, timing and co-ordination. Special considerations are also needed for carbon dioxide removal technologies. |

**Policy tools**

| Economic viability | Lead times | Innovation gaps | Project complexity |
|---|---|---|---|
| ❑ **Grants, tax credits, loans**<br>❑ **State-owned enterprises**<br>❑ **Carbon pricing and leakage policy**<br>❑ **Public procurement**<br>❑ **Low-emissions mandates**<br>❑ **(Carbon) contracts-for-difference**<br>❑ **Regulated asset base**<br>❑ **Emerging market and developing economy considerations:** concessional finance, sustainable debt, multilateral funding instruments | ❑ **One-stop shop for permitting**<br>❑ **Clear approval timelines**<br>❑ **Internal regulatory capacity**<br>❑ **Precompetitive resource assessments**<br>❑ **Data sharing and transparency**<br>❑ **Community engagement requirements** | ❑ **Research, development and demonstration**<br>❑ **Platforms for international co-operation**<br>❑ **Foreign direct investment for technology co-development** | ❑ **Long-term liability legislation**<br>❑ **Competitive solicitations for hubs**<br>❑ **One-off backstop agreements for first movers**<br>❑ **London Protocol specifications**<br>❑ **Definition of high-quality removals**<br>❑ **Monitoring, reporting and verification mechanisms** |

# Chapter 1: Setting the context

## Overview

Carbon capture, utilisation and storage (CCUS) is an important suite of technologies for the decarbonisation of the energy system towards global net zero emissions by 2050. CCUS technologies can reduce emissions in some industrial sectors in which emissions are hard to abate, where other technology options are limited or not yet mature (e.g. cement, iron and steel, chemicals). They can also enable low-emissions hydrogen production, supporting the decarbonisation of other parts of the energy system, including industry and long-distance transport. Moreover, CCUS technologies can facilitate the continued operation of existing industrial and power plants, avoiding early and potentially costly retirement of valuable assets. Finally, CCUS technologies can remove $CO_2$ from the air through bioenergy with carbon capture and storage (BECCS) and direct air capture with storage (DACS).

**What is CCUS and how does it work?**

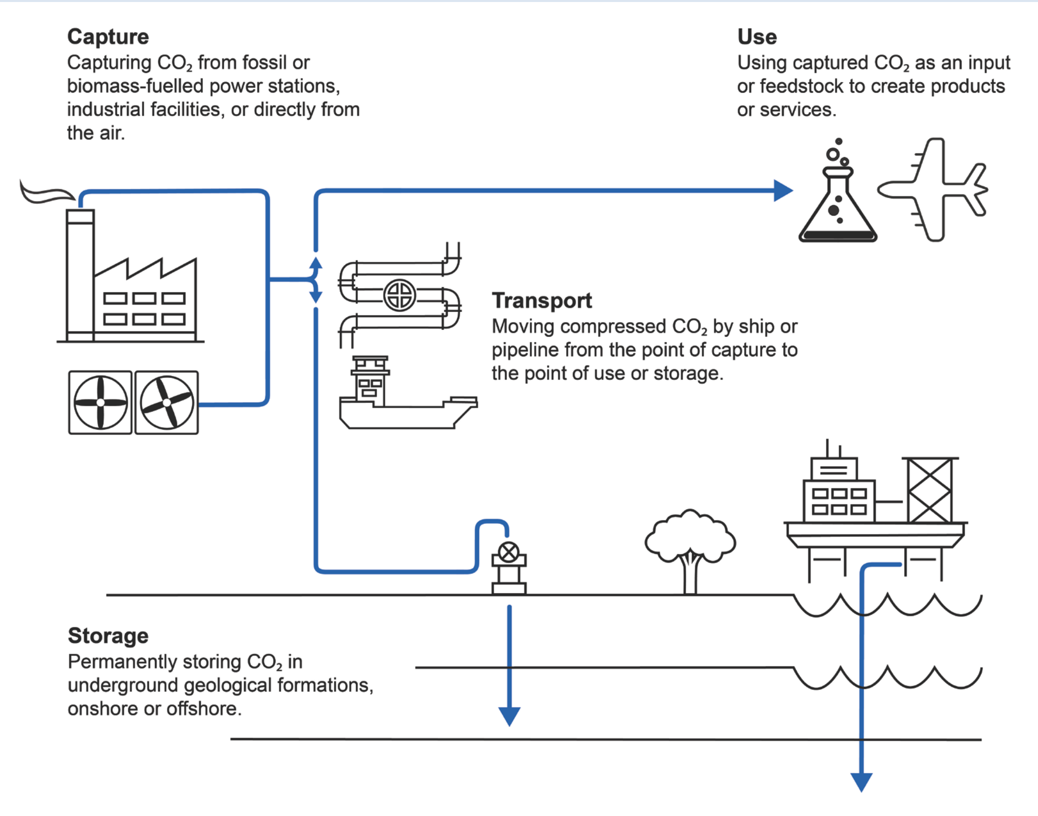
CCUS involves the capture of $CO_2$, generally from large point sources such as industrial or power generation facilities that use either fossil fuels or biomass as fuel, or from the air. If not being used on-site, the captured $CO_2$ is compressed and transported by pipeline, ship, barge, rail or truck to be used in a range of industrial applications (e.g. synthetic fuels, building materials), or injected into deep geological formations such as saline formations, depleted oil and gas reservoirs or unconventional storage resources (e.g. basalts, peridotites) for permanent storage.

CCUS technologies are particularly well suited for applications where alternative decarbonisation methods are not technically or commercially available, such as heavy industry and carbon removal. They are one of the few options available for addressing industrial process emissions, and they can also help to balance the intermittency of renewable energy through the decarbonisation of base load power generation.

While $CO_2$ use can deliver climate benefits, it is a complement rather than an alternative to $CO_2$ storage, which is expected to be deployed at a much larger scale in order to reach international climate goals. In the IEA Net Zero Emissions by 2050 Scenario (NZE Scenario), around 95% of total captured $CO_2$ (across all CCUS applications) is destined for $CO_2$ storage rather than use.

Carbon dioxide removal (CDR) can balance out residual emissions from sectors such as heavy industry and long-distance transport. Technology-based CDR includes BECCS and DACS. BECCS involves capturing and permanently storing $CO_2$ from processes where biomass (which extracts $CO_2$ from the atmosphere as it grows) is refined or burned to generate energy. DACS involves the capture of $CO_2$ directly from ambient air (as opposed to a point source) for permanent storage. These technology-based approaches are part of a much broader CDR portfolio including nature-based solutions (such as afforestation and reforestation) and enhanced natural processes (such as biochar and enhanced weathering). Bioenergy with carbon capture and direct air capture are also able to supply $CO_2$ that is not fossil-based for $CO_2$ utilisation.

**Schematic of a potential $CO_2$ management value chain**






Notes: $CO_2$ transport can also include barges, train and tank trucks.

In this report:

- **Carbon capture and storage (CCS)**: includes applications where the $CO_2$ is captured and permanently stored. This includes DACS and BECCS.
- **Carbon capture and utilisation (CCU) or $CO_2$ use**: includes applications where the $CO_2$ is captured and used, for example in the production of fuels

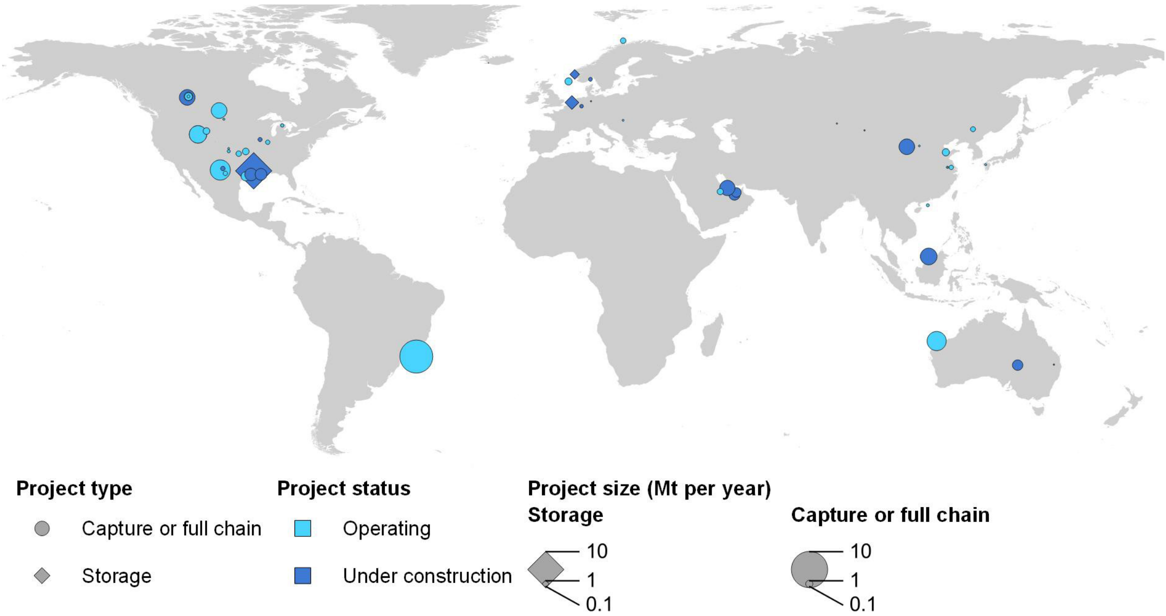
and chemicals. This includes both bioenergy with carbon capture and direct air capture for $CO_2$ utilisation.

- **Carbon capture, utilisation and storage (CCUS)**: includes CCS, CCU, as well as applications where the $CO_2$ is both used and stored, for example in enhanced oil recovery (EOR) or in building materials, where the use results in some or all of the $CO_2$ being permanently stored.

From a commercial perspective, $CO_2$ separation technologies have been successfully implemented and operated for decades where it makes commercial sense to do so, for instance to separate $CO_2$ from methane after it is extracted from a natural gas reservoir, or to separate $CO_2$ from hydrogen during ammonia production (in order to produce urea). Despite the first CCUS projects having been operational since the 1970s and 1980s, progress towards CCUS as a climate change mitigation approach has been slow. The lack of dedicated revenue streams, incentives and regulations for carbon capture applications aimed at emissions reduction has translated into low deployment of CCUS for dedicated $CO_2$ storage purposes. Of the 41 facilities capturing $CO_2$ today,[2] only 9 are transporting $CO_2$ to dedicated $CO_2$ storage sites, while the remainder are injecting the $CO_2$ for the purpose of increasing production from depleting oil fields through EOR, or for other industrial uses.

[2] Includes the Petra Nova plant in the United States which resumed operation in September 2023.

**Large-scale CCUS projects, operating and under construction, 2023**



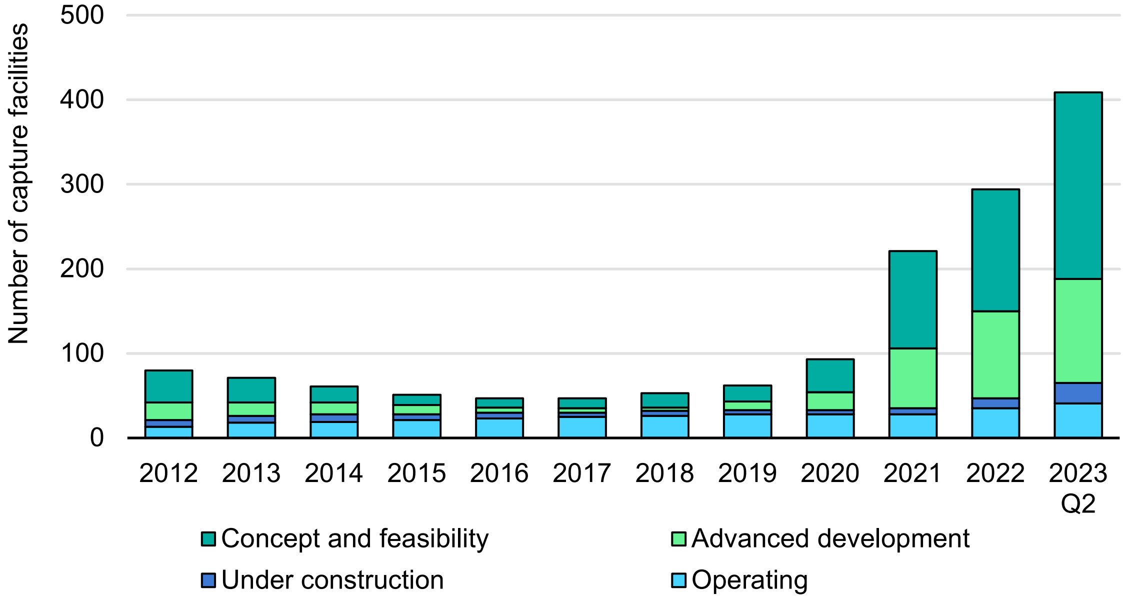



Notes: Large-scale refers to a capture capacity equal to or above 100 000 t $CO_2$/yr (or 1 000 t $CO_2$/yr for direct air capture applications). Storage includes both dedicated $CO_2$ storage and $CO_2$-enhanced oil recovery (EOR). While most of the $CO_2$ injected for EOR is retained in the reservoir over the life of the project, additional monitoring and verification is required to confirm that the $CO_2$ has been permanently stored.
Source: IEA (2023), CCUS Projects Database.

Some progress has been recorded during the past five years, with over 500 projects currently in development globally across the entire CCUS value chain, and new policies to support commercial deployment being proposed. While this positive momentum is encouraging, even if all these projects materialise into operating plants, they would only represent just over a third of what is needed in 2030 to get on track with the NZE Scenario.[3] Achieving the 2030 level of global deployment of CCUS in the NZE Scenario hinges on planned projects reaching completion, as well as a reduction in project lead times, which currently average around 6 years.[4] Adoption of best practices could compress lead times to around 3 to 4 years, if $CO_2$ transport and storage infrastructure is already in place. On a global scale, if the current momentum continues until 2026 and project lead times (from announcement to operation) decrease to around 4 years on average,[5] the 2030 deployment target in the NZE Scenario could be achieved.

[3] This report is based on an updated and revised NZE Scenario, which sets out a pathway for the global energy sector to achieve net zero $CO_2$ emissions by 2050.
[4] Project lead time is defined here as the total time required between conception and commissioning of a facility.
[5] Please refer to the section "Long lead times" for the assumptions behind this estimate.

**Evolution of the $CO_2$ capture project pipeline, 2012-Q2 2023**






Notes: Includes commercial-scale projects with a capture capacity over 100 000 t $CO_2$/yr (or 1 000 t $CO_2$/yr for direct air capture applications). Includes capture projects for dedicated storage, enhanced oil recovery (EOR), and use as long as $CO_2$ is used in fuels, chemicals, polymers, building materials, or for yield boosting. Within planned industrial clusters, only identified $CO_2$ capture projects are included (not the full potential capture capacity of industrial clusters for which capture sources are not specified). ''Under construction'' also includes projects which have reached a final investment decision (FID) and for which construction is imminent.

Source: IEA (2023), CCUS Projects Database.

# Net zero pledges and the role of CCUS

The number of countries that have pledged to achieve net zero emissions has grown rapidly over the past few years. When the IEA released its landmark Net Zero by 2050 report in 2021, our analysis showed that pledges at that time – even if implemented in full and on time – would still put the world on a path to 2.1°C of warming by the end of the century, missing the goals of the Paris Agreement and hugely increasing climate risks.

Since then, countries have raised their ambitions and more have pledged to reach net zero by 2050 or soon after. Our updated analysis of these new targets – on top of all of those made previously – shows that if they are met in full and on time, they would be enough to hold the rise in global temperatures to 1.7°C by the end of the century. As of October 2023, 93 countries plus the European Union have pledged to meet a net zero emissions target. Representing more than 85% of global energy-related $CO_2$ emissions, these net zero pledges are either enshrined in legislation (i.e. legally mandated), mentioned in a policy document, or announced.

Governments are increasingly recognising the role that CCUS can play in achieving their net zero ambitions. Of the countries with a net zero pledge in place, around half have identified CCUS as contributing in some way to the target, though there is a wide range across countries. For example, some countries see CCUS as a key pillar of economy-wide decarbonisation, including CCUS as an option to decarbonise the power and industrial sectors. Others see CCUS as having a very limited role, such as focusing only on cement decarbonisation, or technology-based carbon removals, or restricting CCUS activities to R&D efforts.

This is also reflected in some countries' Nationally Determined Contributions (NDCs) under the Paris Agreement. While the level of detail can vary considerably across NDCs, more than 15 NDC submissions (out of 168) include CCUS.[6] Among them, only Saudi Arabia and Bahrain explicitly mention direct air capture (DAC).

### Countries with a net zero target explicitly mentioning CCUS

| Country | Target Year | Legally Mandated | CCUS in NDC |
|---|---|---|---|
| Guyana | Achieved | No | No |
| Finland | 2035 | Yes | No |
| Iceland | 2040 | Yes | Yes |
| Germany | 2045 | Yes | No |
| Nepal | 2045 | No | No |
| Sweden | 2045 | Yes | No |
| Australia | 2050 | Yes | Yes |
| Cambodia | 2050 | No | No |
| Canada | 2050 | Yes | Yes |
| Denmark | 2050 | Yes | No |
| France | 2050 | Yes | No |
| Greece | 2050 | Yes | No |
| Hungary | 2050 | Yes | No |
| Ireland | 2050 | Yes | No |
| Italy | 2050 | No | No |
| Japan | 2050 | Yes | Yes |
| Korea | 2050 | Yes | No |
| Latvia | 2050 | No | No |
| Lithuania | 2050 | No | No |
| Malta | 2050 | No | No |
| Morocco | 2050 | No | Yes |
| Netherlands | 2050 | Yes | No |
| New Zealand | 2050 | Yes | No |
| Norway | 2050 | No | Yes |
| Oman | 2050 | No | No |
| Singapore | 2050 | No | No |
| Slovak Republic | 2050 | No | No |

[6] Australia, Bahrain, Canada, China, Egypt, Iceland, Iran, Japan, Morocco, Norway, Pakistan, Saudi Arabia, Türkiye, United Arab Emirates, United Kingdom, United States and Viet Nam.

| Country | Target Year | Legally Mandated | CCUS in NDC |
|---|---|---|---|
| Slovenia | 2050 | No | No |
| South Africa | 2050 | No | No |
| Spain | 2050 | Yes | No |
| Sri Lanka | 2050 | No | No |
| Switzerland | 2050 | Yes | No |
| Tunisia | 2050 | No | No |
| United Arab Emirates | 2050 | No | Yes |
| United Kingdom | 2050 | Yes | Yes |
| United States | 2050 | No | Yes |
| Viet Nam | 2050 | No | Yes |
| Türkiye | 2053 | No | Yes |
| Bahrain | 2060 | No | Yes |
| China | 2060 | No | Yes |
| Ghana | 2060 | No | No |
| Indonesia | 2060 | No | No |
| Kazakhstan | 2060 | No | No |
| Saudi Arabia | 2060 | No | Yes |
| Ukraine | 2060 | No | No |
| Thailand | 2065 | No | No |
| India | 2070 | No | No |
| Nigeria | 2070 | Yes | No |

Notes: New Zealand has only identified direct air capture as a possible removal solution; Sweden only identifies biogenic carbon capture as a possible removal solution; Slovenia's net zero goal is under proposed legislation; Malta has identified $CO_2$ use as a promising research area.

Source: IEA Climate Pledges Explorer and Clean Air Task Force.

In step with the recognition of CCUS in net zero plans, governments are also starting to issue **carbon management and CCUS strategies** to signal how they intend to deploy CCUS and in what areas. These strategies, which may also include specific $CO_2$ capture or storage targets, can be in the form of technology roadmaps or high-level plans. In other cases, such as in Denmark and the Netherlands, these strategies are enshrined in broader legislation or political strategy. There are currently at least six strategies in place – all of which have been published in the past few years – and at least another five in development.

### Selected carbon management and CCUS strategies

| Government | Strategy Name | Specific Target or Capacity | Status |
|---|---|---|---|
| Canada | Carbon Management Strategy | 2030: 16.3 Mt $CO_2$/yr | Published |
| Denmark | Agreement on Strengthened Framework Conditions for CCS in Denmark | No specific target, but the strategy expects around 3.2 Mt $CO_2$/yr by 2030 | Published |
| Japan | CCS Long-Term Roadmap | 2030: 6-12 Mt $CO_2$/yr<br>2050: 120-140 Mt $CO_2$/yr | Published |
| Netherlands | National Climate Agreement | No specific target, but the strategy set an initial cap at 7.2 Mt $CO_2$/yr by 2030 | Published |
| United Kingdom | CCUS Net Zero Investment Roadmap | 2030: 20-30 Mt $CO_2$/yr | Published |

| Government | Strategy Name | Specific Target or Capacity | Status |
|---|---|---|---|
| United States | Strategic Vision | | Published |
| European Commission | Industrial carbon management strategy | | In development |
| France | CCUS Strategy | 2030: 4-8.5 Mt $CO_2$/yr<br>2050: 15-20 Mt $CO_2$/yr | In development |
| Germany | Carbon Management Strategy | | In development |
| India | 2030 Roadmap for CCUS for Upstream E&P [exploration and production] Companies | | In development |
| Türkiye | Carbon Dioxide Capture and Utilization Technologies Roadmap and Implementation Plan | | In development |

Notes: This does not represent an exhaustive list; in the case of Denmark and the Netherlands, the strategy is enshrined in broader legislation rather than a separate documented implementation plan; the Netherlands' strategy originally suggested a 7.2 Mt $CO_2$/yr cap for its subsidy scheme, however this cap was then increased and subsequently removed in terms of Mt/yr; Canada's capacity in 2030 represents a point-in-time estimate based on existing policy commitments and assumptions regarding the timing of project investment decisions, approvals and construction.

# Is CCUS on track?

## Overall deployment

Today, more than 45 countries have CCUS projects in development. If all announced capture projects are built, around 400 Mt $CO_2$ could be captured every year globally by 2030 – more than eight times current capacity. Currently, around 65% of operating $CO_2$ capture capacity is at natural gas processing plants, one of the lowest-cost $CO_2$ capture applications, but new CCUS developments are increasingly targeting other applications. Based on the current project pipeline, by 2030 annual capture capacity from both new construction and retrofits could amount to around 80 Mt $CO_2$ from hydrogen production, around 80 Mt $CO_2$ from power generation and around 35 Mt $CO_2$ from industrial facilities (e.g. cement and steel production). Planned capacities for $CO_2$ transport and storage have also increased. Based on the current project pipeline, $CO_2$ storage capacity could reach more than 430 Mt $CO_2$ per year by 2030.

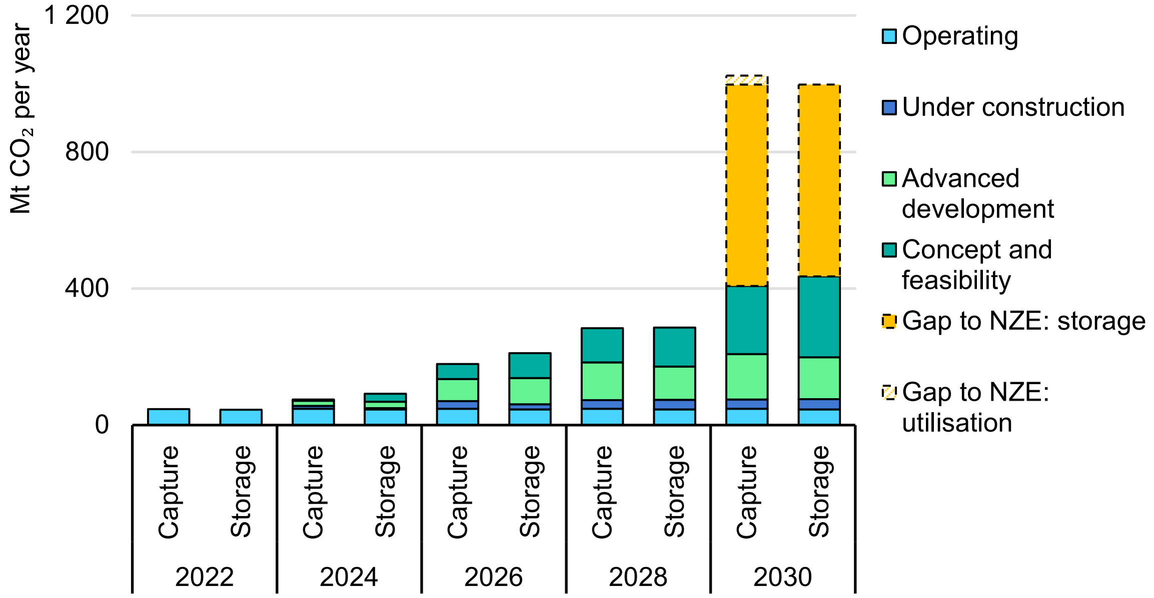
Despite recent momentum, deployment of CCUS projects has been very slow over the longer term, to a large extent due to the lack of policies and business cases that would make investment possible. This points to the need for a more comprehensive approach to policy-making for CCUS. The lack of progress has led to progressive downward revisions of the role of CCUS in climate mitigation scenarios, including the updated NZE Scenario.

## Gap between announced deployment and the NZE Scenario

Despite the recent surge in CCUS announcements for capture, transport, storage and full-chain projects, it is still the case that CCUS deployment by 2030 would remain substantially below (little more than one-third of) the around 1 Gt $CO_2$ per year that is required in the NZE Scenario. This gap between the CCUS project pipeline and the 2030 NZE Scenario deployment target highlights the urgent need for further industry efforts and policy support.

While announcements indicate that the balance between dedicated $CO_2$ storage supply and planned demand based on capture capacities for 2030 can level out globally, gaps could emerge on a regional scale, particularly given the long lead times associated with developing new $CO_2$ storage resources. In the absence of further efforts to accelerate $CO_2$ storage development through government or private sector resource assessment, the availability of well-characterised $CO_2$ storage sites could become a bottleneck to CCUS deployment.

**Capacity of current and planned large-scale $CO_2$ capture and storage projects vs. the Net Zero by 2050 Scenario, 2022-2030**




IEA. CC BY 4.0.

Notes: NZE = Net Zero Emissions by 2050 Scenario. The difference between $CO_2$ captured and stored in 2030 in the NZE Scenario is due to $CO_2$ captured for utilisation in synthetic fuel production. Storage includes both dedicated $CO_2$ storage and $CO_2$-enhanced oil recovery (EOR). While most of the $CO_2$ injected for EOR is retained in the reservoir over the life of the project, additional monitoring and verification is required to confirm that the $CO_2$ has been permanently stored.
Source: IEA (2023), CCUS Projects Database.

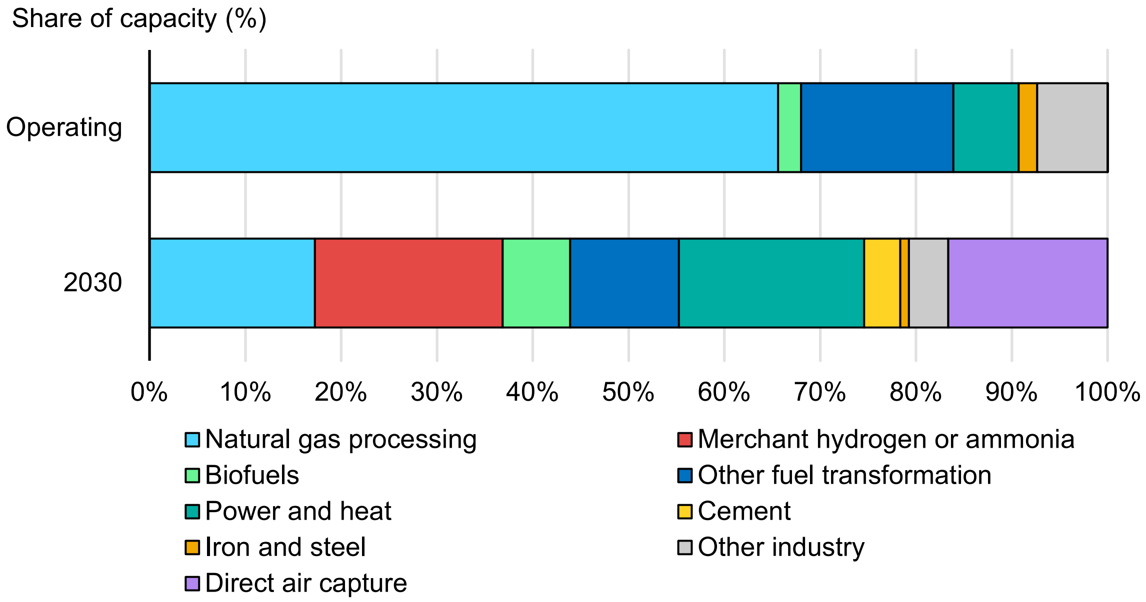
## $CO_2$ capture applications are diversifying

There are now 41 commercial capture facilities in operation globally, applying CCUS to industrial processes, fuel transformation and power generation. Global capture capacity culminates at just over 45 Mt $CO_2$/yr. Most installed capture capacity is associated with natural gas processing (65% of total operational capture capacity), followed by hydrogen production in fertiliser, refining and coal-to-gas plants (25%), and coal-based power (5%).

So far, project developers have announced ambitions to reach over 400 Mt $CO_2$ per year of installed capture capacity by 2030. Based on the current project pipeline, capture applications are likely to diversify over time: by 2030 the share of annual capture capacity from both new construction and retrofits could amount to 20% from merchant hydrogen and ammonia production, 20% from power generation, 15% from DAC and 8% from industrial facilities (mostly cement and chemicals production).

On the other hand, only around 25 commercial capture projects under development (6% of planned capacity for 2030) have taken a final investment decision (FID)[7]. CCUS is one of the main decarbonisation pillars required to get on track towards net zero, and its large-scale deployment is therefore necessary. However, it is currently not cost competitive, not financeable and not even legal for many applications and regions. The gap between planned deployment and needed level by 2030 is particularly pronounced for industry and power generation (see Capture Dashboard).

**Operating and planned $CO_2$ capture capacity by application, Q2 2023 vs. 2030**






Note: Merchant hydrogen or ammonia excludes on-site hydrogen production in industry (included in other industry or other fuel transformation).
Source: IEA (2023), CCUS Projects Database.

[7] Project updates are as of Q2 2023, with the exception of major project updates which include projects (re)entering operation or construction, which are included up to October 2023.

## More countries are developing CCUS projects

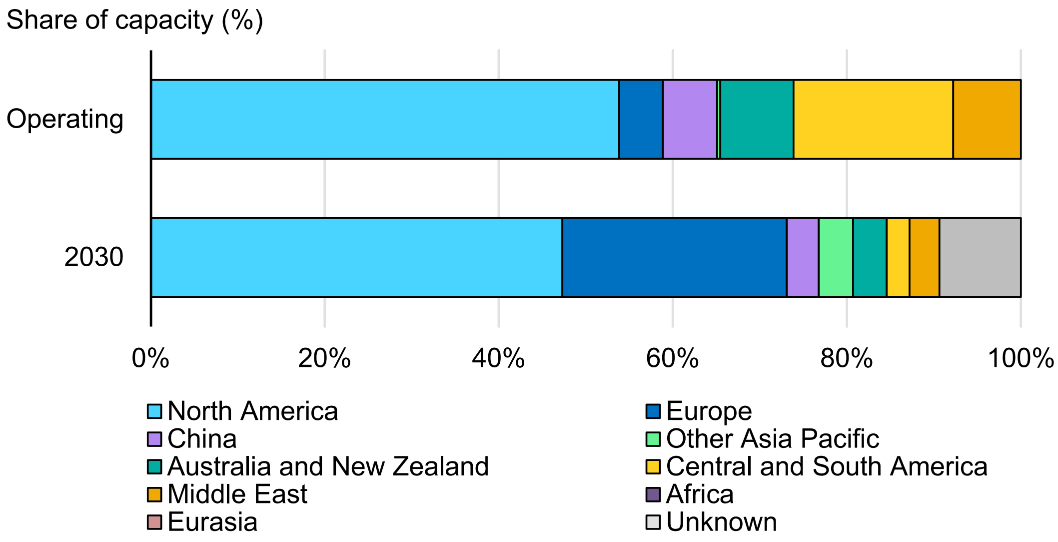
Plans for $CO_2$ capture facilities are expanding globally. Currently, 90% of operational capacity is located in the United States, Brazil, Australia, the People's Republic of China (hereafter China), Canada and Qatar. Out of the four CCUS projects that became operational during the first half of 2023, three are based in China,[8] while one is based in the United States.[9] The United States also hosts three of the five largest capture facilities,[10] while the largest is in Brazil,[11] and the third largest plant[12] in Australia. However, the geographic distribution of $CO_2$ capture projects in development is diversifying, with projects now being developed in more than 45 countries.

Advanced economies are contributing substantially to the total number of announced projects to 2030, with North America and Europe together making up over 70% of planned capacity by 2030. In contrast, emerging economies are lagging behind, with little over 10% of planned capacity by 2030 (with the large majority of it to be located in China, Indonesia and the Middle East). Good progress has been made in the Asia Pacific region (where around 20 capture projects have been announced since January 2022, which would bring total capture capacity to around 45 Mt $CO_2$ per year by 2030) and the Middle East (where around 10 projects are in development across the region, in addition to the 3 already in operation).

Many advanced economies have recently proposed new policies to support CCUS deployment, including the Infrastructure Investment and Jobs Act and the Inflation Reduction Act in the United States, the CCUS Investment Tax Credit in Canada, the Net Zero Industry Act in the European Union, the 2023 Spring Budget in the United Kingdom, and the CCS Roadmap in Japan. On the other hand, despite emerging economies having the youngest industrial and power fleets, they are typically trailing behind on CCUS with only a few countries taking steps towards deployment. Examples include Indonesia, which has adopted the first CCUS legal and regulatory framework in Southeast Asia, and a few new operational projects in China. As first-of-a-kind CCUS hubs are firing up in advanced economies, there is a need to translate business models and policies for emerging economies.

[8] China Energy Taizhou power plant, CNOOC Enping offshore CCS plant, Jiling Petrochemical CCUS plant
[9] Global Thermostat headquarters plant.
[10] The Century plant in Texas, and the original plant and expansion of the Labarge Shute Creek Gas Processing Plant in Wyoming.
[11] Petrobras Santos Basin pre-salt oilfield EOR project.
[12] Gorgon CCS.

**Operating and planned $CO_2$ capture capacity by region, Q2 2023 vs. 2030**





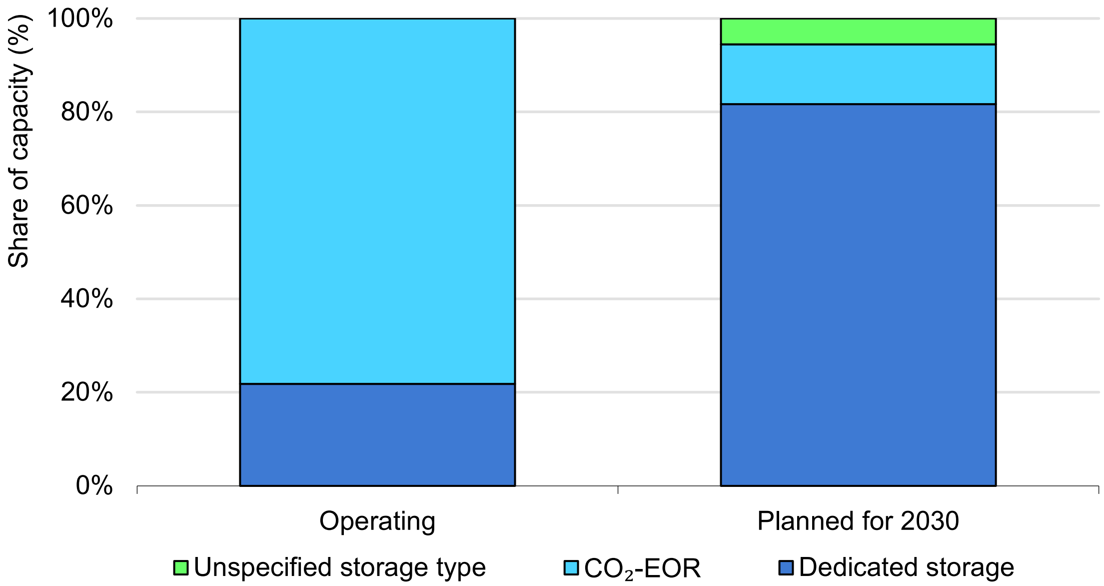

Note: ''Unknown'' refers to company announcements with no disclosed location.
Source: IEA (2023), CCUS Projects Database.

## Development of dedicated $CO_2$ storage accelerates

Over the past year, there has been a large acceleration of dedicated geological storage development. Total planned storage capacity has more than doubled since January 2022, reaching over 430 Mt $CO_2$/yr by 2030. Generally, this provides a positive outlook for CCUS, signalling strengthened market conditions driven primarily by policy implementation and co-ordinated alignment of the CCUS value chain by operators.

A monumental shift from EOR towards dedicated $CO_2$ storage in the near future is a sign of strengthened action towards net zero commitments. Today, just over 10 Mt $CO_2$/yr of captured $CO_2$ is injected for dedicated storage within nine commercial-scale sites, but based on the project pipeline, dedicated storage capacity could increase to over 350 Mt $CO_2$/yr by 2030. The substantial move away from EOR (from around 80% of capacity today to little over 10% of capacity in 2030) towards dedicated storage is driven by a combination of factors, including the recognition of CCUS in facilitating the transition to net zero (see previous section Net zero pledges and the role of CCUS) and the dedicated storage requirements in some policies in order to receive public funding (see Chapter 2).

**Operating and planned $CO_2$ storage facilities by type of storage, 2023**






Notes: EOR = enhanced oil recovery. While most of the $CO_2$ injected for EOR is retained in the reservoir over the life of the project, additional monitoring and verification is required to confirm that the $CO_2$ has been permanently stored.
Source: IEA (2023), CCUS Projects Database.

## Increasing options for $CO_2$ transport

There are at least 14 500 km of $CO_2$ pipelines currently under different stages of development around the globe, as well as many projects that are yet to disclose their planned pipeline length. In the United States, in addition to the approximate 9 000 km of operating pipeline that is transporting around 70 Mt of $CO_2$ annually, three cross-state pipeline projects across the Upper Midwest region had been planned to collectively add nearly 6 000 km of new pipeline to the existing infrastructure network. However, recent rejections of permit applications have created setbacks for these projects, and resulted in the cancellation of the Heartland Greenway pipeline (planned to be longer than 2 000 km). In Europe, multiple cross-border infrastructure projects are being developed to access storage resources in the North Sea. In March 2023 Wintershall Dea and Fluxys jointly proposed a major open-access $CO_2$ transmission network to connect industrial clusters in Germany to Belgium's Zeebrugge Port, with capacity to transport 30 Mt $CO_2$/yr. There are also plans for an onshore carbon transit grid that will serve as a collection point at the Zeebrugge port to facilitate onwards transport for storage in the North Sea by the offshore Belgium-Norway trunk line (1 000 km). This joint venture between Equinor and Fluxys will aim to transport 20 to 40 Mt $CO_2$/yr.

In addition to pipeline development, shipping is also considered to be an economical option that provides access for first-comer emitters to offshore trunklines. Incremental expansion of multi-user transport networks can be an attractive approach for project investors when there are demand uncertainties for such a service – as is the case for the Northern Lights transport network[13] in Norway. The project will consist of shipping (initially three dedicated $CO_2$ vessels, each with a capacity of 7 500 $m^3$, to transport 1.5 Mt $CO_2$/yr) and an offshore pipeline (100 km with a capacity of 5 Mt $CO_2$/yr).

In early 2023, in Denmark, the pilot phase of Project Greensand pioneered the first cross-border $CO_2$ shipment from Belgium to an offshore depleted oil field in the Danish North Sea for storage. This project – notably facilitated by the first-ever bilateral agreement of its kind – highlights a landmark achievement that paves the way for future cross-border $CO_2$ transportation and storage, especially given that the London Protocol has thus far been posing a significant barrier to transnational export and storage of $CO_2$.

# CCUS dashboards

Following the 2023 Net Zero by 2050 report, the dashboards below present the major milestones for the main CCUS steps (capture, transport, storage) and technologies on the pathway to reach net zero emissions from the global energy sector by 2050.

[13] Northern Lights is the transport and storage part of the Longship CCS project.

## Capture

- 41 capture facilities in operation worldwide capturing around 45 Mt $CO_2$ per year.
- 7 new plants coming online since January 2022 in China, the United States and Europe.
- Around 400 Mt $CO_2$ of capacity planned for 2030.
- United States and Europe lead capture developments, but over 10 projects announced in China, the Middle East and Southeast Asia since January 2022.
- Less than 10% of planned capture capacity has reached a final investment decision.

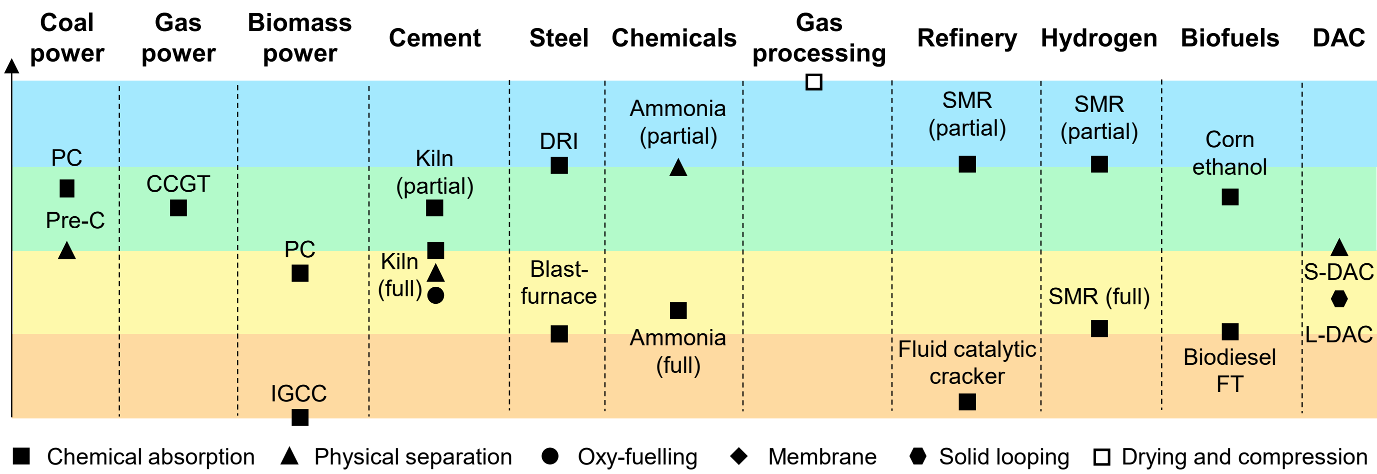
### Deployment by sector

| Mt $CO_2$ per year | 2023 | 2030 | |
|---|---|---|---|
| | | Planned | NZE |
| Power | 3 | 79 | 233 |
| Cement | 0 | 15 | 167 |
| Other industry | 4 | 20 | 104 |
| Natural gas processing | 31 | 70 | 92 |
| Biofuels | 1 | 28 | 114 |
| Hydrogen | 0 | 80 | 161 |
| Other | 8 | 46 | 74 |
| DAC | 0.01 | 68 | 80 |

### Deployment by region

| Mt $CO_2$ per year | 2023 | 2030 | |
|---|---|---|---|
| | | Planned | NZE |
| Advanced economies | 32 | 316 | 471 |
| Emerging economies | 15 | 53 | 553 |
| Unknown | 0 | 38 | 0 |
| *North America* | 26 | 192.5 | |
| *Europe* | 2 | 105.0 | |
| *China* | 3 | 14.9 | |
| *Middle East* | 4 | 14.0 | |
| *Rest of the world* | 13 | 80.3 | |

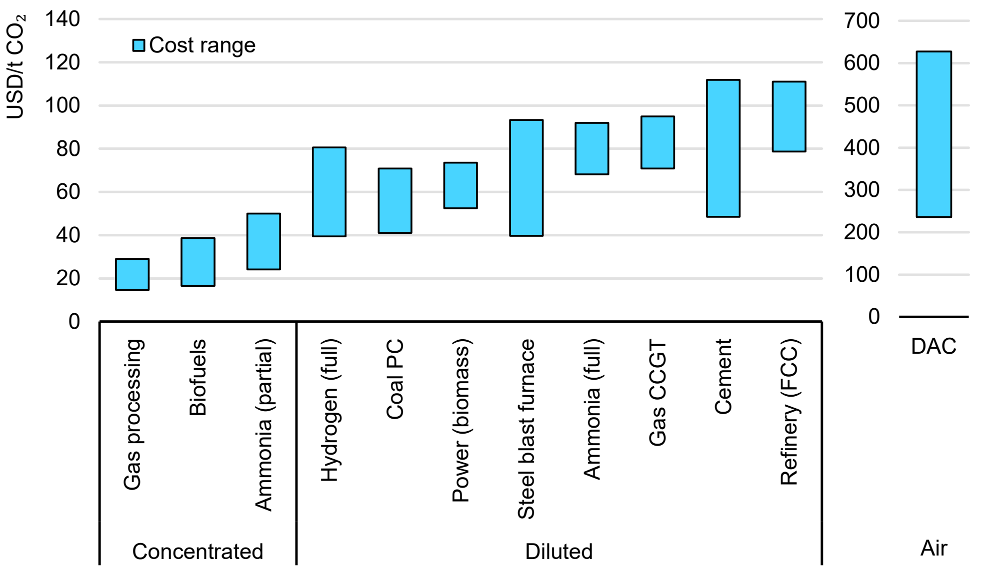
### Technology Readiness Level (selected technologies)




### Costs

Costs depend on:

- $CO_2$ concentration in the gas stream
- Number of points of capture
- Capture technology
- Capture efficiency/rate
- Energy source and heat integration
- Retrofit or new-build
- Scale
- Impurities in stream.



# Storage

- More than 390 Mt of new annual $CO_2$ storage capacity announced since January 2022.
- Total planned storage capacity has more than doubled since January 2022, reaching around 430 Mt $CO_2$/yr by 2030.
- Planned global storage capacity of $CO_2$ for 2030 is currently greater than planned capture.
- $CO_2$ storage projects are shifting away from EOR towards dedicated storage.

## Deployment by storage type

| Mt $CO_2$ per year | 2023 | 2030 | |
|---|---|---|---|
| | | Planned | NZE |
| Total | 45 | 435 | 997 |
| Dedicated | 10 | 355 | |
| EOR | 35 | 55 | |
| Unspecified/unknown | 0 | 49 | |

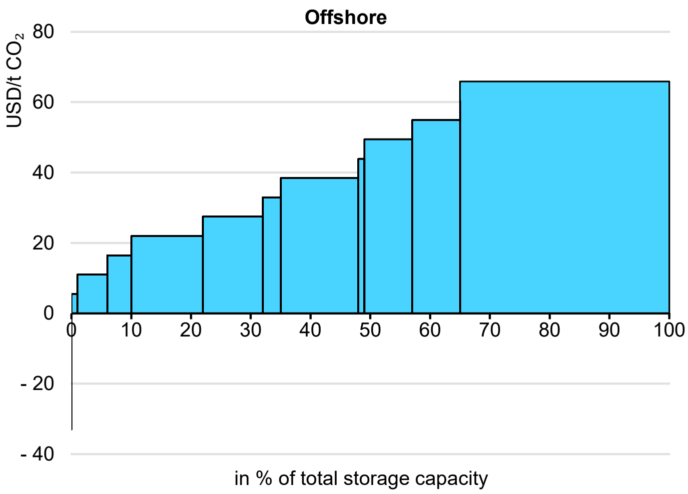
## Deployment by region

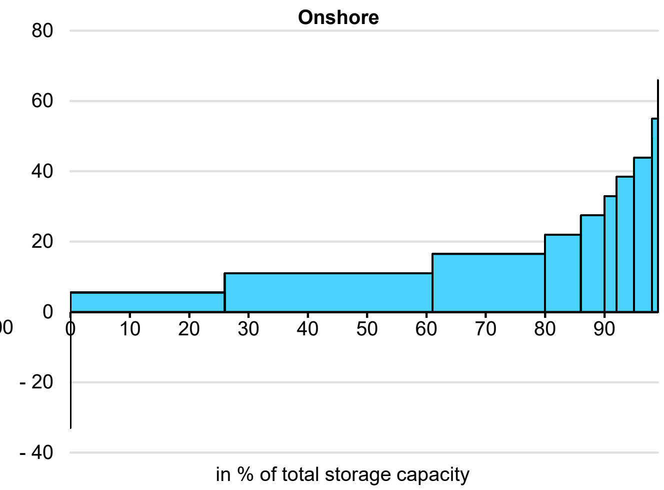
| Mt $CO_2$ per year | Planned for 2030 | |
|---|---|---|
| | Capture | Storage |
| North America | 190 | 165 |
| Europe | 101 | 143 |
| China | 13 | 13 |
| Middle East | 14 | 23 |
| Rest of the World | 79 | 91 |

## Technology Readiness Level

| | TRL | Notes |
|---|---|---|
| Depleted fields | 7-8 | The first injection of $CO_2$ within depleted fields has been completed in 2023 during the pilot phase of Project Greensand in the Danish North Sea. |
| Saline aquifers | 9 | $CO_2$ injection in saline aquifers has been successfully demonstrated over the past two decades with many operational large-scale first-of-a-kind projects around the world (e.g. Sleipner in Norway, Quest in Canada). |
| Dissolved $CO_2$ injections | 5 | Aqueous injections, where $CO_2$ is dissolved in water and injected into mafic igneous rocks, have been demonstrated by Carbfix in Iceland. In Oman, two pilots have been conducted injecting $CO_2$ dissolved in rainwater into peridotite formations for accelerated mineralisation and sequestration of $CO_2$. |
| Advanced monitoring technologies | 7-8 | Advanced monitoring technologies, such as offshore seismic monitoring methods are currently being demonstrated as part of project Greensand in Denmark. They provide an alternative solution for taking seismic surveys more efficiently than traditional methods. |

## Costs




Key cost factors include:

- Location, which determines accessibility and the unique site characteristics, i.e. the geology
- Existing infrastructure (e.g. platforms, wells) that can be used
- Uncertainty in storage-specific regulations
- Social acceptance
- Contingencies to compensate for uncertainties in flow behaviour.

| Projects | Capacity (Mt $CO_2$/yr) | Capital cost (USD million) |
|---|---|---|
| Sleipner | 1 | 180 |
| Snøhvit | 0.7 | 260 (initial) + 275 (mitigation) |
| Gorgon | 4 | 2240 |
| Quest | 1.2 | 100 |

## Transport

- Multi-user CCUS hubs are gaining momentum over the world, with around 90 dedicated $CO_2$ transport projects (some including storage) in planning.
- North Sea region: around 40 dedicated transport projects in planning, and the pilot phase of Project Greensand pioneered the first cross-border $CO_2$ shipment in early 2023. Construction is underway for the first $CO_2$-receiving terminal and three dedicated $CO_2$ ships (Northern Lights project) in Norway, for commissioning in 2024.
- North America: nearly 9 000 km of $CO_2$ pipeline in operation and around 20 projects in planning. New pipeline developments are facing social opposition with Heartland Greenway recently cancelled following permit rejection.
- Asia Pacific: around 20 transport projects in planning, including plans for cross-border shipping between Singapore and Australia, and Japan, Australia and Malaysia.

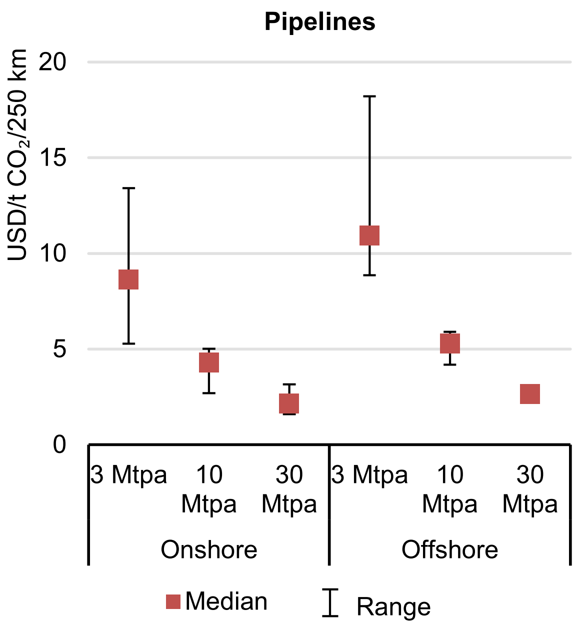
### Deployment

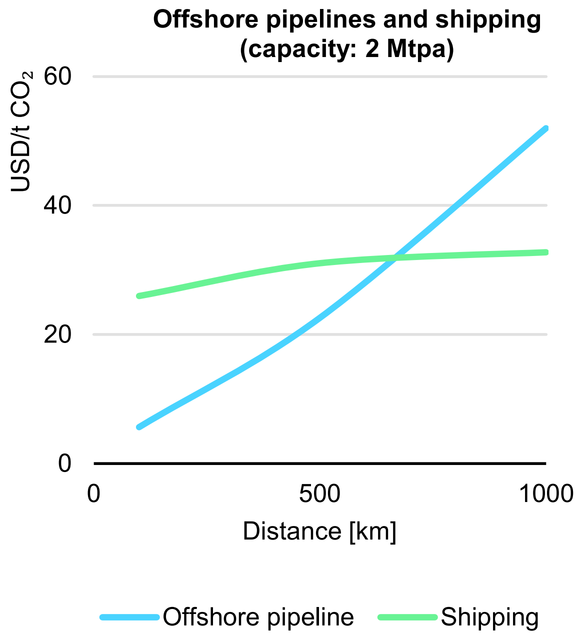
| km | 2023 | 2030 | |
|---|---|---|---|
| | | Planned | NZE |
| Pipelines | 9 500 | > 14 500 | 30 000 – 50 000 |

### Technology Readiness Level (selected technologies)

| | TRL | Notes |
|---|---|---|
| Pipelines | 10 | $CO_2$ pipelines have been extensively used for EOR, and more recently for dedicated storage, with around 9 500 km deployed. |
| Shipping | 6-7 | Low-volume $CO_2$ vessels are operating around the world at median pressure (15 bar) for the food industry. Three 7 500 m³ and medium pressure ships operating are being built for the Northern Lights project. Higher volume ships (e.g. 40 000-70 000 m³) operating at lower pressure (7 bar) are currently at prototype scale. |
| Rail | 6-7 | The Morecambe Net Zero Cluster in the United Kingdom plans to transport $CO_2$ from the Peak cluster via rail. |

### Costs




Pipeline capacity is the leading factor influencing cost. Costs decrease from USD 9-11/t $CO_2$ for a 3 Mt $CO_2$/yr pipeline down to USD 2-3/t $CO_2$ for a 30 Mt $CO_2$/yr pipeline over 250 km distance.
Other factors impacting transport costs include:

- Distance
- Mode of transport (e.g. pipeline, ship, truck, barge)
- Transport condition of $CO_2$
- Topology

| Projects | Capacity (Mt $CO_2$/yr) | Length (km) | Unit cost (USD/t $CO_2$/yr) |
|---|---|---|---|
| Quest | 1.2 | 80 | 30 |
| Alberta Carbon Trunk Line | Operating: 1.6 | 240 | 2 |
| | Design capacity: 15 | 240 | 21 |

## CCUS hubs

CCUS projects in development now increasingly follow a ‘’many-to-many’’ deployment model, where capture projects are developed as part of CCUS hubs that consist of shared transport and storage infrastructure connecting multiple emitters (often part of an industrial cluster). There are now at least 110 storage hubs in development around the world, with plans to sequester around 280 Mt $CO_2$ per year by 2030, mainly in Europe and North America, with a few examples starting to emerge in Asia and the Middle East as well.

**Selected storage hubs in development by region, 2023**

| Region/country | Number of storage hubs in development | Total storage capacity in planning by 2030 (Mt) | Total storage capacity in planning (Mt) |
|---|---|---|---|
| North America | 59 | 107 | 192 |
| Europe | 29 | 134 | 219 |
| Australia and New Zealand | 12 | 14 | 52 |
| Japan | 4 | 8 | 8 |
| China | 4 | 6 | 16 |
| Indonesia | 1 | 0 | 0 |
| Saudi Arabia | 1 | 9 | 9 |
| Malaysia | 1 | 2 | 2 |
| **Total** | **112** | **279** | **500** |

Source: Analysis based on IEA (2023), CCUS Projects Database.

The CCUS hub model spreads infrastructure costs between emitters and generates economies of scale, allowing emitters that are smaller in scale or farther away from identified $CO_2$ storage sites to still be able to connect to the common infrastructure. The mainstreaming of this model could also help reduce lead times, as new capture facilities could connect to an existing CCUS hub in around 3 to 4 years.

Large trunklines with under-used $CO_2$ infrastructure capacity are available and planned in some regions. Depending on location, this can enable a greater number of small-scale emitters to consider $CO_2$ capture a feasible option for decarbonising their operations. Examples of major pipeline networks run by specialist operators where this may be possible include:

- The 240 km Alberta Carbon Trunk Line (ACTL) in Canada, owned and operated by Wolf Midstream since 2020, transports 1.6 Mt $CO_2$/yr from two industrial sources for utilisation and permanent storage. With a design capacity of around 15 Mt $CO_2$/yr, ACTL was developed with excess capacity to connect more facilities in the future. In September 2023, Wolf Midstream announced that a new 40 km pipeline extension is underway, the "Edmonton Connector", which will expand the ACTL network into the Edmonton region to enable greater emissions-reduction opportunities. This includes an agreement with Air Products to transport $CO_2$ from their new, under construction, Net Zero Hydrogen Energy Complex.

- In continental Europe, multiple cross-border infrastructure projects are being developed to access storage resources in the North Sea. The latest announcement, from March 2023, includes a major open-access $CO_2$ transmission network jointly proposed by, Wintershall Dea and Fluxys to connect industrial clusters in Germany to Belgium's Zeebrugge Port.

Despite the numerous advantages of the hubs and clusters model, this approach also comes with challenges related to the co-ordination of the various steps of the chain and the various players (see Chapter 4). Moreover, a non-negligible share of dispersed and small-scale applications are unlikely to be within a reasonable distance of industrial clusters and therefore less likely to benefit from economies of scale in connecting to the storage hub. Finally, CCUS hubs relying on oversized transport and storage infrastructure increase counterparty risk for transport and storage developers, potentially making it harder for those projects to get financing.

# The IEA CCUS Handbook series

Meeting net zero goals will require a rapid scale-up of CCUS globally, from tens of millions of tonnes of $CO_2$ captured today to over a billion of tonnes by 2030. A small number of countries alone cannot meet this goal, and getting on track with a net zero emissions future will require a truly global effort.

The IEA CCUS Handbook series aims to support the accelerated development and deployment of CCUS by sharing global good practice and experience. The handbooks provide a practical resource for policy makers and stakeholders across the energy industry to navigate a range of technical, economic, policy, legal and social issues for CCUS implementation.

This handbook aims to provide governments with a policy toolkit to build a commercial market for CCUS. Policies to date have allowed the existing fleet of projects to move into operation, but a more holistic view of the challenges facing CCUS deployment is needed in order to deploy at the pace and scale required in the NZE Scenario. Overcoming these challenges is entirely possible with the right policy environment and investment from industry.

Chapter 2 provides a comprehensive list of existing policies to facilitate and promote CCUS deployment, highlighting country examples across five macro-categories of policies. Chapter 3 outlines emerging business model trends for CCUS, including how both new and old players are working to split up and specialise across the CCUS value chain. Chapter 4 identifies the major challenges to large-scale CCUS deployment, including economic viability, long lead times, innovation gaps and project complexity. Finally, keeping in mind these emerging business model trends and overarching challenges to deployment, Chapter 5 presents a policy toolkit to aid governments in establishing an economically sustainable market for CCUS deployment, in developed as well as emerging economies.

This is the third in the IEA CCUS Handbook series and complements the handbooks on Legal and Regulatory Frameworks for CCUS and on $CO_2$ Storage Resources and their Development. As such, this handbook does not go into great detail on the legal and regulatory considerations for enabling CCUS deployment, nor does it cover the technical and process matters associated with developing $CO_2$ storage. We refer those interested in these topics to the other handbooks.

# Chapter 2: Policy trends

## Overview

Initial deployment and scale-up of energy technologies generally requires some level of risk-sharing between the public and private sectors to get first projects off the ground and eventually create an economically sustainable and viable market. Successful policy frameworks for energy technologies have typically relied on multiple, sustained layers of support that work by sharing risks between the public and private sectors and increasing the value proposition of the technology.

Governments around the world have taken different approaches to supporting carbon capture, utilisation and storage (CCUS) projects. Some have taken a broad approach that is not focused on a particular project, while others have concentrated incentives on a few selected projects.

As a start, including CCUS in climate and energy policies can send a clear signal to investors and project developers on the importance and strategic value of CCUS. From there onwards, governments have a range of policy mechanisms available to support the deployment of projects. These can be broadly classified into five general categories: **enabling legislation and rules**, **cost reduction measures**, **regulation of industrial activities**, **strategic signalling** and **revenue support**. Every country with an operating CCUS project has at least one of these policy mechanisms currently in place, and countries with a healthy project pipeline tend to have multiple mechanisms in place or in planning.

While the latter four mechanisms focus on promoting and encouraging CCUS deployment, the first (enabling legislation and rules) *facilitates* by creating the enabling conditions necessary for CCUS activities.

These policy mechanisms generally apply to projects within a country's borders, especially if public funds are used. For example, public funding to reduce the cost of CCUS typically requires the funding recipient to be located within that country. However, there can be exceptions to this in some countries if part of the CCUS project's value chain is linked to the funding country. For example, in June 2023 the Japan Organization for Metals and Energy Security (JOGMEC) selected seven CCUS projects to support financially, two of which would transport $CO_2$ that is captured in Japan to other countries for storage. Other examples include the European Union's Innovation Fund and Connecting Europe Facility. The types of policy mechanisms that more commonly include international aspects are regulation of industrial activities, which can include carbon pricing programmes that extend beyond a country's borders, and enabling legislation and rules, which can have specifications for the cross-border transport and storage of $CO_2$.

There is no one-size-fits-all solution when it comes to policy-making for CCUS, but projects tend to have the most success when countries put in place multiple layers of policy support.

### Current policy mechanisms for CCUS

| Category | Types and Description |
|---|---|
| **Enabling legislation and rules** | This mechanism facilitates and provides a platform for CCUS deployment. **Legal and regulatory frameworks** set a legal basis for CCUS activities and ensure the safe and secure storage of $CO_2$. Nearly every operating CCUS project has benefited from the establishment of a legal and regulatory framework. |
| **Cost reduction measures** | Government support can reduce the capital and/or operating costs of CCUS projects. This is a common mechanism that has been applied to many operating projects to date.<br><br>**Grants** are a common financing mechanism that have been used by the majority of CCUS projects to date and can help fund expensive activities such as feasibility or Front-End Engineering and Design (FEED) studies. Grant funding can also drive advances in R&D and innovation.<br><br>Governments can also provide loan support, such as through **preferential interest rates, access to debt capital** and **loan guarantees**.<br><br>**Tax credits** can reduce costs by allowing projects to recover capital or operating costs associated with investment in qualified equipment or per tonne of $CO_2$ stored.<br><br>For some countries, **partially or fully state-owned enterprises** (SOEs) have been directly involved in CCUS projects. This can indirectly reduce costs by allowing the public sector to manage more of the investment risks. |
| **Regulation of industrial activities** | Putting a price on $CO_2$ can incentivise emitters to invest in technologies to reduce emissions. This can be in the form of a **carbon tax** or through carbon markets, such as an **emissions trading scheme**, where facilities are penalised for emitting $CO_2$ or other GHGs, encouraging investment in emissions-reduction technologies. |
| **Strategic signalling** | Governments can send strategic signals that work to incentivise long-term investment in CCUS projects. For example, **deployment targets** that outline a certain level of desired CCUS capacity can communicate a government's clear intention. |
| **Revenue support** | Newer policy mechanisms that seek to provide a predictable revenue stream for CCUS projects are being considered, such as **(carbon) contracts-for-difference** and the **regulated asset base model**. While these mechanisms have been used for other clean energy technologies, they are now being tested in some countries for CCUS. |

Source: For more information on policies and measures to support CCUS please visit the IEA Policies and Measures (PAMS) database.

# Existing CCUS policies

In total, around 15 countries have CCUS policies on the books that go beyond R&D initiatives. A roughly equal number of countries have CCUS projects in operation.

Two policy mechanisms in particular have commonly supported CCUS projects in operation: **enabling legislation and rules** and **cost reduction measures**. In advanced economies, enabling legislation and rules (through the establishment of legal and regulatory frameworks for CCUS) have provided the necessary platform for the first projects storing $CO_2$ at dedicated sites. In addition, cost reduction measures in some countries, such as one-off grants to specific projects and tax credits for the storage or use of $CO_2$, have moved projects to a point where they could start operation. In emerging markets and developing economies (EMDEs), as well as some advanced economies, cost reduction measures have been seen through state-owned enterprises (SOEs) that offload investment risks from the private sector.

This has had a noticeable impact on the types of applications where CCUS is deployed. As shown in Chapter 1, most of the installed $CO_2$ capture capacity (two-thirds) is associated with natural gas processing, one of the lowest-cost $CO_2$ capture applications. This is, in part, a function of the *types* of policy mechanisms that governments have employed over the years: enabling legislation and rules and certain cost reduction measures incentivise the “low-hanging fruit” (i.e. the lowest-cost applications) first. As a result, the gap in deployed projects is particularly pronounced for higher-cost applications such as power generation and industry (see the Capture dashboard).

At the same time, governments have also implemented regulations on industrial activities to promote emissions-reduction technologies – commonly through carbon pricing programmes. However, in practice these programmes have shown that carbon pricing on its own (if too low and too volatile) is not enough to incentivise CCUS deployment.

Deployment of CCUS beyond low-cost applications requires several, if not all, types of policy mechanisms. Experience has shown that enabling frameworks and cost reduction policies are the minimum needed to get projects off the ground, but a global scale-up of CCUS at the rate required in the Net Zero Emissions by 2050 Scenario (NZE Scenario) requires policies to support revenue, strategic targets to signal long-term commitment and regulation of industrial activities to drive market demand.

Moving forward, the CCUS project pipeline shows a greater diversity in $CO_2$ capture applications as well as a greater geographic distribution of projects. This partially reflects government action to propose policies that fit across all categories. In fact, for countries with CCUS projects in the pipeline but no projects currently in operation, policies tend to span multiple mechanisms.

### Existing CCUS policy mechanisms by country

| Country | Operational and planned capture capacity (Mtpa) | Enabling legislation and rules | Cost reduction measures | Regulation of industrial activities | Strategic signalling | Revenue support |
|---|---|---|---|---|---|---|
| United States | 21 (operation)<br>140 (planned) | X | X | | | |
| Brazil | 8.7 (operation)<br>0.4 (planned) | | X | | | |
| Australia | 4 (operation)<br>11 (planned) | X | X | X | | |
| Canada | 4.1 (operation)<br>27 (planned) | X | X | X | X | |
| China | 3 (operation)<br>12 (planned) | | X | X | | |
| Qatar | 2.1 (operation)<br>2.9 (planned) | | X | | | |
| Norway | 1.7 (operation)<br>2.8 (planned) | X | X | X | | |
| Saudi Arabia | 0.8 (operation) | | X | | | |
| United Arab Emirates | 0.8 (operation)<br>7.4 (planned) | | X | | | |
| Japan | 0.2 (operation) | | X | | X | |
| United Kingdom | 57 (planned) | X | X | X | X | X |
| Netherlands | 14 (planned) | X | X | X | X | |
| Indonesia | 10 (planned) | X | X | X | | |
| France | 4.7 (planned) | X | X | X | X | |
| Denmark | 1.8 (planned) | X | X | X | X | |

Notes: Planned capture capacity only includes projects with an announced timeline before 2030 and clearly identified facilities. Countries in grey do not have any operating CCUS projects at the time of publication. Countries that only fund CCUS R&D are not included. The United States does not have a carbon pricing programme at the national level, but there are various carbon pricing programmes at the state level. Countries in the European Union are eligible for EU cost reduction programmes and are required to implement the European Union's carbon pricing and regulatory framework – as such only countries with support mechanisms in addition to those of the European Union are included. Australia previously provided cost reduction support to CCUS projects, though this funding programme has since been cancelled and replaced by a smaller programme to support emerging $CO_2$ capture and utilisation in sectors where emissions are hard to abate.

## Enabling legislation and rules

Enabling legislation and rules provide a supportive environment for CCUS and act as a platform to build from. This policy mechanism facilitates CCUS deployment, rather than promotes. It often involves the establishment of legal and regulatory frameworks for CCUS that provide a legal basis for the effective stewardship of CCUS activities and the safe and secure storage of $CO_2$.

Several countries have already developed comprehensive legal and regulatory frameworks for CCUS. These form a valuable knowledge base for the growing number of countries that have identified a role for CCUS in meeting their climate goals, but which are yet to establish a legal foundation for CCUS, and particularly for $CO_2$ storage. Over 20 jurisdictions (subnational, national or regional) have legal and regulatory frameworks in place for CCUS projects. Indonesia is one of the most recent countries to put a legal framework in place for $CO_2$ storage, and Brazil is working to finalise its first framework for dedicated $CO_2$ storage.

### Legal and regulatory frameworks of selected countries

| Country | Policy |
|---|---|
| **European Union** | The CCS Directive establishes the legal framework in the European Union for geological storage of $CO_2$. The state assumes responsibility of the $CO_2$ storage site following a minimum 20-year period from the closure of the site, and only after the storage operator provides evidence indicating that the stored $CO_2$ will be completely and permanently contained, and that there has been a financial transfer which covers monitoring costs for approximately 20 years. |
| **Canada** | Canada does not have a comprehensive regulatory framework for $CO_2$ storage in federal jurisdictions, but the provinces of Alberta, British Columbia and Saskatchewan have frameworks in place to support safe and secure geological $CO_2$ storage. Other provinces, such as Manitoba, Ontario and Nova Scotia, are taking steps towards developing enabling frameworks for $CO_2$ storage. |
| **United States** | The legal framework for $CO_2$ storage in the United States is based in the country's underground drinking water legislation, and only applies to pore space that is privately owned or under state jurisdiction; there is no legal framework for $CO_2$ storage in federal jurisdiction (onshore and offshore). As such, there is no transfer of liability at the federal level, though operators are required to monitor the $CO_2$ storage site for up to 50 years after its closure.<br><br>Several states have their own legal frameworks for CCUS on top of the federal requirements. This includes Indiana, Kansas, Louisiana, Montana, Nebraska, New Mexico, North Dakota, Texas and Wyoming. Out of the nine states with a framework, six have provisions for the transfer of site ownership or liability to the government after the storage site is closed. |
| **Australia** | In Australia, the legal framework for $CO_2$ storage only applies to offshore areas within the federal government's jurisdiction, while states and territories have their own legal frameworks for onshore and offshore storage. Queensland, South Australia and Victoria have comprehensive CCUS frameworks in place, while Western Australia has specific legislation to enable the Gorgon project. |
| **United Kingdom** | The United Kingdom's legal framework follows the European Union's CCS Directive, including the transfer of responsibility to the government after a 20-year period following the closure of the $CO_2$ storage site. |
| **Japan** | Japan currently does not have a legal framework for $CO_2$ storage, however it is in the process of designing legislation to enable the country to start storing $CO_2$ by 2030. |
| **Indonesia** | Indonesia's framework is based in its upstream oil and gas regulation. Holders of oil and gas leases are allowed to store $CO_2$ within existing leasing areas, such as in depleted oil and gas fields. The framework allows for the capture of $CO_2$ outside of the oil and gas industry, but the $CO_2$ must ultimately be stored in a lease area. In addition to the technical and legal requirements needed to ensure safe and secure $CO_2$ storage, the framework also outlines several business and economic aspects. For example, the framework outlines potential pathways to monetising carbon credits for the project and its partners. In addition, the framework outlines conditions under which storage operators may grant third-party access to storage facilities. |

Source: IEA (2022), CCUS Legal and Regulatory Database.

## Cost reduction measures

Energy projects tend to be capital-intensive and to involve large amounts of up-front investment. To reduce these costs, governments can provide **grants**, **loans** and **tax credits**. Cost reduction measures such as these are the most common policy mechanism employed by governments and can cut across several different policy programmes in a given country. Another cost reduction measure that governments can take is through the involvement of **SOEs**. By including SOEs in CCUS projects, costs are indirectly reduced by shifting some of the investment risk associated with the project to the public sector.

**Grants** are a direct financial contribution that can either be provided specifically to targeted projects or through competitive programmes. While grants can cover various upfront costs of CCUS projects, such as construction costs, several countries have targeted grant funding for feasibility and Front-End Engineering and Design (FEED) studies. A FEED study is a comprehensive (and often costly) effort that requires significant engineering and design work to inform whether or not a project moves forward. Grants have also been used to fund geological storage atlases to identify potential $CO_2$ storage resources.

Governments can also provide **loan support** to projects for which the commercial lending sector might not be as active. This can be an effective policy tool for clean energy technologies such as CCUS that have difficulty accessing debt from private lenders. This can be in the form of providing **debt capital** (i.e. a direct loan) with **preferential rates** or via **loan guarantees** (whereby the government promises to purchase the debt from the private lending institution and take on responsibility for the loan in the event that the borrower defaults).

**Tax credits** are a common policy mechanism to promote specific behaviours or encourage the adoption of certain practices, technologies or equipment. A tax credit allows an individual or company to subtract an amount of money directly from the taxes that they owe (i.e. their tax liability). For example, an **investment tax credit** allows the company to subtract a certain percentage of its investment costs in a project from its tax liability. Well-designed tax credits can allow for the transfer of the credit to other project partners (for instance, if the company receiving the credit does not have a high enough tax liability it may be eligible to pass the credit to an investor in exchange for financing). Further, refundable investment tax credits for CCUS projects can be paid to the taxpayer as a refund in situations where the credit exceeds the taxpayer's liability or in the absence of any tax liability. This is expected to benefit earlier stage companies that do not yet have the taxable income to benefit from a non-refundable investment tax credit. Canada is now finalising the details of its investment tax credit for CCUS, which was first proposed in 2021. In 2023, Malaysia proposed an investment tax credit for CCUS. In addition to covering capital expenditures, tax credits can also cover operating expenses, or – in the case of CCUS projects – provide a credit amount for the amount of $CO_2$ stored on a per tonne basis. Currently this form of tax credit for CCUS projects is only available in the United States.

In the Netherlands, the Stimulation of sustainable energy production and climate transition (SDE++) subsidy scheme provides subsidies for qualifying clean energy technologies. For CCUS projects, the subsidy is awarded to the capture project over a 15-year period and bridges the cost gap between production with CCUS and without CCUS, linked to the carbon price under the EU emissions trading system (ETS). Under the SDE++ the project operator is not required to pay the government back should the EU ETS price go above the operator's production costs – in this case, the project would no longer require public funding as the carbon price would be enough to cover the project's costs. Under the scheme, four emitters associated with the Porthos projects were selected to receive up to EUR 2.1 billion (USD 2.5 billion), and eight emitters associated with the Aramis project were selected to receive up to EUR 6.7 billion (USD 7 billion).

## Cost reduction policies

| Country | Policy |
|---|---|
| **European Union**<br>✓ Grant<br>Tax credit<br>✓ Loan | The Innovation Fund provides regular grants that support up to 60% of a low-carbon technology project's costs, with up to 40% of the grant available to projects before operation, provided certain milestones are met. The Fund has issued three funding calls each for large-scale (capital costs above EUR 7.5 million [USD 8.2 billion]) and small-scale projects, awarding over EUR 1.7 billion (USD 1.9 billion) to 15 projects with a CCUS component since 2020. The third large-scale funding call selected seven CCUS projects, though the exact funding amount for each has yet to be announced. Norway and Iceland are also eligible under this fund.<br><br>The Connecting Europe Facility (CEF) awards grants to cross-border energy, transport and digital infrastructure projects that connect two or more member states. $CO_2$ transport and storage infrastructure (including pipelines, storage facilities linked to cross-border transport of $CO_2$, and fixed facilities for liquefaction and buffer storage) are eligible for funding. Early CEF funding for CCUS projects focused on feasibility studies, with more recent funding allocated to FEED studies and infrastructure development. In total, nearly EUR 300 million (USD 334 million) has been allocated to CCUS projects since 2020, with the largest amount of funding given to the Antwerp@C $CO_2$ Export Hub project (EUR 145 million [USD 152 million]) and the Porthos project (EUR 102 million [USD 117 million]).<br><br>The Recovery and Resilience Facility is the European Union's stimulus package in response to the COVID-19 pandemic, and provides over EUR 700 billion (USD 828 billion) to member states in the form of grants and loan support. CCUS projects are eligible for grants under seven member state plans approved by the European Commission. |
| **United States**<br>✓ Grant<br>✓ Tax credit<br>✓ Loan | The Infrastructure Investment and Jobs Act (IIJA) provides approximately USD 12 billion for CCUS through 2026. This includes USD 937 million for large-scale $CO_2$ capture pilot projects, USD 2.5 billion for $CO_2$ capture demonstration projects, USD 2.5 billion for large-scale $CO_2$ storage projects and associated transport infrastructure, USD 75 million for $CO_2$ storage permitting, and USD 3.5 billion for regional direct air capture (DAC) hubs. The funding under the IIJA for CCUS is mainly in the form of cost-shared grants.<br><br>The 45Q tax credit provides projects with a credit of up to USD 85/t $CO_2$ permanently stored and USD 60/t $CO_2$ used or through EOR, provided emissions reductions can be clearly demonstrated. The credit amount significantly increases for DAC projects to USD 180/t $CO_2$ permanently stored and USD 130/t $CO_2$ for $CO_2$ use. There is a direct pay and transferability option for developers who receive the credit, meaning that the developer can monetise the credit or transfer it to project partners or investors with a large enough tax liability.<br><br>The IIJA also establishes the USD 2.1 billion $CO_2$ Transportation Infrastructure Finance and Innovation Act (CIFIA) programme, which will provide loans, loan guarantees and grants to large-capacity $CO_2$ transportation projects. Projects must be common carrier, meaning access to the transportation infrastructure is shared, and non-discriminatory under a publicly available tariff, and have project costs over USD 100 million.<br><br>The United States provides loans and loan guarantees through its Loan Programs Office (LPO) for clean energy and energy infrastructure projects, including CCUS. Eligible projects can receive favourable interest rates, set at the US Treasury rate, plus a liquidity spread and risk-based charge. Although no CCUS projects have received LPO loan support to date, projects across the value chain (including point-source carbon capture, transport, utilisation, and storage, and atmospheric carbon dioxide removal) are eligible. |

| Country | Policy |
|---|---|
| **Canada**<br>✓ Grant<br>✓ Tax credit<br>✓ Loan | The refundable Investment Tax Credit (ITC) is available to CCUS projects that permanently store $CO_2$ with eligible capital expenses at the following rates: DAC equipment (60%), equipment to capture $CO_2$ in all other CCUS projects (50%), and transportation, storage and use equipment (37.5%) from 2022-2030. These rates will be reduced by 50% for the period from 2031 through 2040 to encourage industry to move quickly. The government will also undertake a review of ITC rates before 2030 to ensure that the proposed reduction in rates aligns with the government's environmental objectives.<br><br>The Energy Innovation Program is delivering CAD 319 million (Canadian dollars) (USD 245 million) in funding over 7 years to CCUS RD&D projects, including up to CAD 50 million (USD 38 million) in funding specifically for nine selected CCUS FEED studies.<br><br>The CAD 15 billion (USD 12 billion) Canada Growth Fund is a new arm's length public investment vehicle designed to attract private capital for clean technology and decarbonisation projects, including CCUS. When established, it will have at least four distinct investment offerings for projects: concessional equity or debt, contracts-for-difference, anchor equity and offtake contracts.<br><br>The Canada Infrastructure Bank invests in CCUS infrastructure projects, including through its Project Acceleration funding for FEED capital expenditures.<br><br>The Net Zero Accelerator initiative is providing up to CAD 8 billion (USD 6.5 billion) over 7 years to support large-scale investments in clean technologies, including CCUS. The Strategic Innovation Fund under this initiative includes funding for CCUS deployment projects.<br><br>At the provincial level, Alberta's Carbon Capture and Storage Fund is providing CAD 1.24 billion (USD 95 million) in grant funding for up to 15 years to the Quest and Alberta Carbon Trunk Line (ACTL) projects. Up to 40% of the funds were allocated before operation, provided certain milestones were met, another 20% of the funds were allocated upon commencement of operations, and the final 40% will be disbursed during operation for up to 10 years. Additionally, Emissions Reduction Alberta has invested over CAD 160 million (USD 123 million) in CCUS projects, which includes grant funding for pre-construction studies, while the Industrial Energy Efficiency and CCUS Program provides grants that cover up to 75% of project costs (up to a CAD 20 million [USD 15 million] maximum) – with CAD 40 million (USD 30 million) to date related to CCUS projects. |
| **United Kingdom**<br>✓ Grant<br>Tax credit<br>Loan | The Carbon Capture and Storage Infrastructure Fund supports the capital costs of strategic CCUS infrastructure through the identification of key clusters. The GBP 1 billion (USD 1.3 billion) fund provides grant funding to $CO_2$ transport and storage networks and early industrial carbon capture projects. Grants for industrial carbon capture projects are capped at up to 50% of total capital costs and are not to be used for pre-FEED and FEED costs.<br><br>The Spring Budget 2023 is providing up to GBP 20 billion (USD 24 billion) for CCUS projects under its cluster sequencing process.<br><br>The Industrial Energy Transformation Fund provides grant funding for feasibility and FEED studies of clean energy technologies, including CCUS. The Fund has announced three phases and to date has issued over GBP 400 000 (USD 500 000) in grant funding to CCUS projects.<br><br>The Industrial Decarbonisation Challenge provides grant funding for feasibility and FEED studies of CCUS and hydrogen industrial clusters from 2019 through 2024. The Challenge has issued over GBP 170 million (USD 234 million) in funding to six large industrial clusters. |
| **Australia**<br>✓ Grant<br>Tax credit<br>Loan | The Carbon Capture Technologies Program provides grants up to AUD 15 million (Australian dollars) (USD 10 million) for RD&D projects that focus on emerging $CO_2$ capture technologies, DAC, bioenergy with CCS and $CO_2$ utilisation technologies, among other areas.<br><br>The Low Emissions Technology Demonstration Fund, now closed, provided funding to demonstrate low-emissions technologies. Chevron's Gorgon project received AUD 60 million (USD 42 million) in funding under this fund. |

| Country | Policy |
|---|---|
| **Denmark**<br>✓ Grant<br>Tax credit<br>Loan | The Energy Technology Development and Demonstration Program (EUDP) provides grants to clean energy projects up to Technology Readiness Level (TRL) 8. The EUDP has funded Project Greensand with DKK 197 million (Danish kroner) (USD 31 million) and Project Bifrost with DKK 75 million (USD 12 million).<br><br>In August 2023, the Danish government proposed a plan to merge two funding pools into two tenders totalling EUR 3.6 billion. Approximately EUR 1.4 billion (USD 1.5 billion) will be allocated to the first tender, which aims to result in 0.9 Mt of stored $CO_2$, and EUR 2.2 billion (USD 2.3 billion) will be allocated to the second tender, which aims to result in 1.4 Mt $CO_2$ stored. The funding will be allocated over a 15-year period, with projects starting in 2029. |
| **Japan**<br>✓ Grant<br>Tax credit<br>Loan | JOGMEC provides financial and technical support to CCUS projects in the form of equity investments, loan guarantees and funding for feasibility studies and storage resource assessments. In June 2023, under its Advanced CCS Projects scheme, JOGMEC selected seven projects to receive funding to reduce project capital costs. Although the exact funding amount for each project has yet to be determined, Japan has allocated an initial USD 25 million to support these projects. |

Notes: Programmes that only focus on R&D are excluded from this table; Technology Readiness Levels (TRLs) are used to measure progress in the development (TRL1-9) and deployment (TRL 9-11) of a particular technology, from concept to market-wide adoption.

In some cases, governments have used their SOE system to deploy or become heavily involved in CCUS projects. This has been a common route in several countries where SOEs already own a significant number of energy and related infrastructure projects, such as in the Middle East and China. Currently, around a dozen projects in operation are owned and operated by an SOE. In China, SOEs Sinopec, PetroChina, CHN Energy and CNOOC own and operate nearly every operating project in the country, with the exception of the Karamay methanol plant operated by the private Dunhua Oil Company. Likewise, in the Middle East, SOEs Saudi Aramco, Qatar Energy (with ExxonMobil) and ADNOC dominate the regional CCUS projects in operation.

In addition to China and the Middle East, Norway has relied heavily on its SOE ecosystem to develop and deploy CCUS projects. For example, the Norwegian Government is the majority shareholder in Equinor, which has nearly three decades of experience operating commercial CCUS projects (e.g. the Sleipner project commissioned in 1996 and the Snøhvit project commissioned in 2008). In addition to Equinor, the Norwegian Government established Gassnova in 2005 as the SOE dedicated to developing CCUS technologies through administrating a research and financing programme and serving as the key government adviser on CCUS. Falling under the Norwegian Ministry of Petroleum and Energy, Gassnova was closely involved in the early planning of the Longship CCS project, producing early phase studies and acting as a project integrator.

## State-owned enterprises involved in CCUS

| Country | SOEs |
|---|---|
| **China** | Sinopec, PetroChina, CHN Energy and CNOOC |
| **Saudi Arabia** | Saudi Aramco |
| **Qatar** | Qatar Energy |
| **United Arab Emirates** | ADNOC |
| **Norway** | Gassnova |

| Country | SOEs |
|---|---|
| **Japan** | JOGMEC |
| **Netherlands** | Energie Beheer Nederland (EBN) and Gasunie |
| **Brazil** | Petrobras |
| **Indonesia** | Pertamina |
| **Thailand** | PTT Exploration and Production |
| **India** | Indian Oil Corporation |
| **Malaysia** | Petronas |
| **Timor-Leste** | TIMOR GAP |

## Regulation of industrial activities

Governments can also promote CCUS deployment through the regulation of industrial activities that seek to reduce emissions from one or multiple sectors. Carbon pricing has been one option within broader climate and energy policy to reduce emissions and help foster clean energy transitions. It can influence the economic choices of investors and technology developers by encouraging emitters to invest in technologies to reduce emissions or face a penalty.

Confidence in rising future carbon prices can be a strong driver for investment in clean energy technologies and their RD&D, but low and volatile carbon prices are not enough to drive long-term investment. Indeed, carbon pricing alone has not been enough to incentivise CCUS projects. The notable exception is in Norway, where the country's carbon tax played an important role in the development of the Sleipner CCS project.

There are two general approaches to putting a price on carbon: a **carbon tax** and **carbon markets**. Under a carbon tax, the government sets a price per tonne of $CO_2$ that emitters must pay. The tax can increase over time, providing a signal to emitters that they will need to invest in technologies that are able to provide substantial emissions reductions. This provides a greater level of certainty about future prices, but governments have less control over the actual level of emissions reduction.

Carbon markets can be further divided into **emissions trading systems** (ETS) and **carbon crediting**. In an ETS, the government typically sets an emissions cap and allocates a certain number of per-tonne allowances to emitters that is consistent with that cap. Emitters covered under the ETS may buy and sell allowances – those that reduce their emissions can sell excess allowances to emitters that are unable to do so. The government lowers the cap over time, so that total emissions fall. In contrast to a carbon tax, an ETS allows the market to determine the price on carbon. It provides a greater level of certainty about future emissions, but not necessarily about the price of those emissions. Of the ETS currently in force, only five have regulations specific to CCUS: those of California, the European Union, New Zealand, Quebec and the United Kingdom.[14]

Each approach can vary in coverage (such as economy-wide or sector-specific) as well as scope ($CO_2$ emissions or other GHGs). As of September 2023, over 70 jurisdictions (subnational, national or regional) have a carbon pricing system in place, roughly equally split between a carbon tax programme and an ETS. In total these carbon pricing systems cover around one-quarter of global GHG emissions. Other countries, such as **China**, **India** and **Japan**, have recently implemented (or will soon implement) a carbon pricing system.

Regardless of the approach, the revenues from a carbon pricing system could be used to fund or finance climate activities (as is the case for the European Union's Innovation Fund) or supportive measures that can offset the cost burden for the most vulnerable consumers and firms.

In addition to carbon pricing, researchers have recently suggested adoption of a "polluter pays" principle, whereby $CO_2$ storage obligations would be placed on fossil fuel suppliers. Known as a carbon takeback obligation, fossil fuel producers and importers would be required to store a percentage of the $CO_2$ generated by the fuels they sell, and this obligation would increase progressively over time.

### Carbon pricing policies of selected jurisdictions

| Country | Policy |
|---|---|
| **European Union**<br>✓ ETS<br>Carbon tax | The EU ETS is the oldest and largest ETS (in revenue terms) operating worldwide and applies to all EU countries as well as Iceland, Liechtenstein and Norway. The ETS covers around 38% of EU GHG emissions and applies to emissions from activities in the power sector, manufacturing industry, and intra-EU aviation. In 2023, the European Union adopted reforms to the ETS, which includes a more ambitious reduction target for the EU ETS sectors of 62% by 2030; the phase-out of free allocation in some sectors accompanied by the phase-in of the Carbon Border Adjustment Mechanism (CBAM); revised parameters for the Market Stability Reserve; the expansion of the EU ETS to cover maritime shipping; a new and separate ETS for buildings, road transport, and additional sectors; and a strengthened commitment to use ETS revenues to address distributional effects and spur innovation.<br><br>According to the EU legal framework, $CO_2$ that is captured and safely stored is considered as "not emitted" under the ETS. Since 2015, capture, transport and storage installations have been explicitly included in the ETS. |
| **Norway**<br>ETS<br>✓ Carbon tax | Norway was one of the first countries to introduce a $CO_2$ tax. The tax covers 63% of Norway's GHG emissions and applies to $CO_2$ emissions from combustion of all liquid and gaseous fossil fuels and incineration of waste, $CO_2$ and $CH_4$ fugitive emissions, and emissions of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Operators covered by the EU ETS are exempt from the carbon tax, except for in offshore oil production activities, domestic aviation and waste incineration (though Norway has its own waste incineration tax). The Norwegian carbon tax was one of the primary drivers behind the Sleipner CCS project, which has been operating since 1996. |

[14] In the case of New Zealand and California, the ETS does not interact directly with CCUS applications.

| Country | Policy |
|---|---|
| **Canada**<br>✓ ETS<br>✓ Carbon tax | Canada requires all provinces and territories to have a carbon pricing system in place that is at least as stringent as the federal carbon pricing system. A federal carbon pricing backstop mechanism is put in place for provinces or territories that do not have a carbon pricing system, or whose system is not aligned with the federal benchmark criteria. The federal mechanism covers 82% of Canada's GHG emissions and consists of two components: a regulatory charge on fuels and an output-based carbon pricing system (OBPS) for industrial facilities greater than 50 000 t $CO_2$ per year.<br><br>The OBPS, which is similar to an ETS, incentivises CCUS by recognising $CO_2$ storage in deep saline aquifers and depleted oil reservoirs, while provinces that have their own carbon pricing systems also provide CCUS incentives. For example, Alberta's amended Technology Innovation and Emissions Reduction (TIER) Regulation provides increasing CCUS support through new credit classes in addition to CCUS investments by the TIER Fund – a fund generated by large-emitter compliance obligation payments.<br><br>There is no cap on emissions under the federal system; instead there is an emissions-intensity or output-based standard by sector. Importantly, the carbon price is set to steadily increase to CAD 170 (USD 130) per tonne of $CO_2$ equivalent (t $CO_2$-e) by 2030. |
| **Australia**<br>✓ETS<br>Carbon tax | The Safeguard Mechanism assigns emissions baselines for over 200 large facilities. The Mechanism covers GHG emissions from facilities emitting over 100 000 t $CO_2$-e/yr in electricity, mining, oil and gas production, manufacturing, transport and waste. Facilities that emit above their baseline must offset the excess emissions. CCUS-equipped facilities that emit below their baseline can earn credits which can be traded with other covered facilities that exceed their baseline. |
| **United Kingdom**<br>✓ ETS<br>Carbon tax | The UK ETS incorporates several elements of the EU ETS, following the United Kingdom's departure from the European Union. It covers 28% of the United Kingdom's emissions and applies to emissions of $CO_2$, nitrous oxide ($N_2O$), and PFCs in energy-intensive industries, the power sector, and aviation within the United Kingdom and European Economic Area. A number of allowances are allocated for free to industrial participants at risk of carbon leakage. The UK ETS will be extended to cover more sectors – domestic maritime transport from 2026 and waste from 2028 – while rolling out a phased removal of free carbon allowances for the aviation industry in 2026. |

Note: EU member states may have carbon pricing policies in addition to the EU ETS. For example, the Netherlands has a carbon tax that applies to industry and is levied for emissions above a certain threshold, which will be reduced annually through at least 2030, in line with Climate Agreement targets. Unlike a traditional ETS, Canada's federal OBPS does not have a cap on emissions; instead there is an emissions-intensity or output-based standard. At the provincial level, several Canadian provinces and territories use a carbon tax system.
Sources: World Bank (2023), Carbon Pricing Dashboard and the International Carbon Action Partnership.

# Strategic signalling

Some policies can highlight strategic areas of interest for governments. Signalling these strategic areas shows the government's long-term commitment and can work to attract investment from the private sector.

One example is a **deployment target**. This has been a common tool that governments use for renewables, for instance setting a goal of reaching a certain deployment capacity or percentage of total generation. For CCUS, this tool is now being used by countries to signal long-term interest in deployment, often expressed in terms of the amount of $CO_2$ stored within a country by a certain date. In general, two types of deployment targets have emerged for CCUS: a specific target (which can be achieved through a combination of policy measures) and a certain level of deployment as the result of a policy. For example:

- The **European Union's** Net Zero Industry Act proposes to set an EU-wide goal to achieve a $CO_2$ injection capacity of at least 50 Mt by 2030. Oil and gas producers have been asked to contribute to the 50 Mt target, calculated pro-rata based on each entity's share in the European Union's crude oil and natural gas production between 2020 and 2023.

- The **United Kingdom** has a goal to capture and store between 20-30 Mt $CO_2$ per year by 2030 and over 50 Mt $CO_2$ per year by 2035.
- **Japan** set a $CO_2$ storage target of 6-12 Mt $CO_2$ per year by 2030 and 120-140 Mt $CO_2$ per year by 2050 under its long-term CCS roadmap.
- **Canada** released its Carbon Management Strategy, which, among other things, projects that at least 16 Mt $CO_2$ could be stored each year by 2030 based on existing policies and assumptions regarding the timing of project investment decisions, approvals and construction.

# Revenue support

Newer policies to provide revenue support for projects are being considered for CCUS. While these policies have not yet contributed to any operating CCUS projects, they are expected to incentivise greater deployment once finalised. Such policies include a **regulated asset base** and **contracts-for-difference**, both of which are expanded upon in Chapter 5.

Governments have used a **regulated asset base model** in the past for various infrastructure-heavy sectors, such as for the transmission and distribution of electricity and the build-out of nuclear power plants, where the private market alone was not enough to attract the needed investment. The basic idea is that a private company can own and operate an infrastructure asset, charging fees to those that use the infrastructure to recoup investment costs. But in order to prevent monopolistic behaviour, the government can put in economic guardrails that can cap prices, revenue or rates of return. No country has implemented this model for CCUS projects yet, though the United Kingdom is working to incorporate it for $CO_2$ transport and storage.

Governments are also considering using a **contracts-for-difference** (CfD) or **carbon contracts-for-difference** (CCfD) scheme to indirectly increase a CCUS project's revenue. Originating in the financial services sector, a CfD was initially used as a hedging strategy to offset the risk of a financial loss on the stock market. While the concept originated in the financial sector, the core concept has been adopted for large-scale clean energy projects to provide stable prices over a long time period. Under a CfD or CCfD, the government and contracting parties agree on a "strike price" with the project operator (either via bilateral negotiations or competitive processes). If the market price of that commodity differs from the agreed strike price, then either the government or the project will need to cover the differences. For CCUS projects, the strike price is a specific amount per tonne of $CO_2$ and the market price is usually the price of electricity (for a CfD) or the price of carbon (for a CCfD). If the market price is below the strike price, then the government pays the project the difference between the actual market price and the strike price. In the case of a two-sided CCfD, if the market price is above the strike price, then the project pays the government for the excess.

The **United Kingdom** has been one of the leaders in deploying a CfD scheme for renewables in the power sector and is now adopting the CCfD mechanism to drive industrial carbon capture deployment and low-emissions hydrogen deployment. The **European Union** has proposed using a form of CfD or CCfD for the allocation of an expanded Innovation Fund from 2022, and both **France** and **Germany** have also announced a CCfD scheme. **Denmark** has indicated that a similar model will be used for a forthcoming subsidy scheme and **Canada** announced that the government would consult on the development of a broad CCfD approach.

# CCUS policy gaps

While certain existing CCUS policies, such as those falling under the categories of enabling legislation and rules and cost reduction measures, have enabled the current fleet of CCUS projects, several remaining gaps in the policy landscape are making it difficult to launch a sustainable commercial market.

## Lack of diverse revenue streams

Revenue streams for CCUS projects are not well established. This makes it more difficult to build a business case for many projects around the world, especially in those regions that do not already offer support to reduce capital and operating costs.

In the absence of stronger policy support, many operating CCUS projects have benefited from revenue supported by EOR. This has helped spark initial projects, but as global reliance on fossil fuels decreases in a net zero future, dedicated $CO_2$ storage (and not EOR) may align better with long-term policy goals – this is already being reflected in the project pipeline (see Chapter 1). In addition, the volatility of oil prices leaves projects vulnerable to fluctuations in global oil prices (see Chapter 3).

## Low demand for low-emissions products

The current policy environment lacks adequate demand-side measures to create a market for low-emissions products enabled by CCUS. Demand for these products can help establish a commercial case, in particular for $CO_2$ captured at facilities that produce iron and steel, cement and fuels, and also for $CO_2$ that is utilised in products. As shown in Chapter 1, these low-emissions products can help decarbonise other parts of the energy system, such as long-distance transport. They can also potentially provide an additional revenue source for projects, addressing the revenue gap identified earlier.

Emitters that capture their $CO_2$ from emissions-intensive processes may be able to sell these products, such as low-emissions iron and steel, cement, chemicals and fuels, at a premium.

Likewise, $CO_2$ that is captured from point sources or removed from the atmosphere could be used as a commodity and sold for its use in other processes where it has a market value. Currently this is done at a very small scale in a number of agricultural, food production and industrial processes. New utilisation pathways, such as the production of $CO_2$-based synthetic fuels, chemicals and building aggregates, are needed to be compatible with the NZE Scenario, but current policies are not enough to spark this demand.

## Lack of standards and certifications for carbon dioxide removal

As shown in Chapter 1, carbon dioxide removal (CDR) is needed to balance out residual emissions from heavy industries and long-distance transport, and specific considerations are needed to ensure that that CDR technologies can participate in policy frameworks.

Direct air capture with storage (DACS) and bioenergy with carbon capture and storage (BECCS) differ from fossil point-source carbon capture projects in that the climate benefits are focused on emissions *removal* and not emissions *reduction*. This is a key distinction that is often not addressed in existing policy frameworks. Specific considerations for removals – such as developing high-integrity mechanisms to monitor, report and certify units of $CO_2$ removal, as well as integration into broader carbon markets – are only at a nascent stage, though some governments are working on this (see Chapter 5).

Strong interest and fast-moving action from the private sector for high-quality carbon removal credits is putting pressure on governments to consider the role of technology-based CDR solutions in their existing carbon pricing schemes. A better understanding of the implications of integrating removal certificates or credits in domestic compliance carbon markets is needed.

# Chapter 3: Business model trends

## Overview

Business models for carbon capture, utilisation and storage (CCUS) used to rely on the "full-chain'' model, characterised by a single project framework with multiple entities responsible for the various steps of the CCUS chain ($CO_2$ capture, transport, and storage). Today, new business models are emerging, often alongside the development of the CCUS hubs approach, and others have the potential to successfully support large-scale CCUS deployment.

Policy-related revenue streams for the full chain business model were very limited and included one-off grant subsidies to recover part of the CAPEX, and low carbon prices, where applicable. Additional potential income was related to selling the captured $CO_2$, mostly to the oil and gas sector for enhanced oil recovery (EOR) (with limited $CO_2$ monitoring undertaken – which was often below the standard for climate-related reporting – and unpredictable revenues strongly tied to the volatile price of oil). While the full-chain business model has some advantages – the main one being simpler co-ordination between various steps of the CCUS chain – it comes with multiple risks associated with each step, plus high complexity (with a need for technical and operational expertise in all fields), as well as high CAPEX.

In order to better manage risk, new business models are now emerging, characterised by separate entities dealing with $CO_2$ capture and with $CO_2$ transport and storage. Governments need to support the deployment of these new models and step in where the private sector struggles to progress. That could be the case when it comes to co-ordinating the various steps of the chain and the various players; planning for transport and storage infrastructure ahead of planning for $CO_2$ capture (due to longer lead times for storage); addressing long-term liability concerns related to $CO_2$ storage; and establishing reliable revenue streams where a profitable market for $CO_2$ management does not yet exist. Part-chain business models are particularly well suited for CCUS applications needed for net zero, as they can allow emitters to outsource capture, transport and storage expertise to specialised companies. For capture, this is particularly relevant for applications where $CO_2$ is not already separated as part of the process (as opposed to natural gas processing for instance, or ammonia), and which require dedicated capture equipment. CCUS hubs can also shorten lead times for connecting to common infrastructure, reduce costs through increased competition within a more specialised corporate landscape and through cost-sharing on infrastructure, and allow more dispersed and smaller emitters to connect to $CO_2$ transport and storage (due to economies of scale).

Increased climate ambitions are moving the needle away from EOR and towards dedicated storage. While $CO_2$ storage is essential for avoiding the release of $CO_2$ into the atmosphere, it still provides very little to no revenue and only in countries with a carbon pricing system in place. Despite this, clear revenue streams from alternative CCU pathways (with evident climate benefits) are still lacking. This is due to a number of reasons, including technologies at a low Technology Readiness Level (TRL), niche markets, and expensive applications and therefore products. As a result, there is a strong need for governments to formulate policies to promote new CCU pathways aligned with international net zero targets, such as for building materials and synthetic hydrocarbon fuels.

### Key elements of a CCUS business model

| Project type | Ownership | Economic rationale | Challenges | Stakeholders |
|---|---|---|---|---|
| Full chain | Public | Public sources | High capital and operating costs | Government |
| Part chain | Private | Grants, tax credits, loan support | Long project lead times | Policy makers |
| Self-capture with third-party $CO_2$ offtake | Public-private partnership | State-owned enterprises | Project complexity | Regulators (including permitting) |
| $CO_2$ transport and storage as-a-service | | Carbon pricing | Innovation gaps | Private sector |
| Capture-as-a-service | | Public procurement of low-emissions products | Co-ordination among various steps and/or players | Project investors and owners |
| | | Public procurement of carbon dioxide removal services | Cross-border transport | Developers and operators |
| | | Private sources | Policy uncertainty | Supply chain contributors |
| | | Direct use of $CO_2$ | Public awareness and acceptance | Civil society and the public |
| | | Low-emissions products | Availability of finance | |
| | | Voluntary carbon markets | Risk management and insurance | |



**How can a value proposition for CCUS technologies be established?**

The term ''business model'' refers to a company's plan for making a profit. It identifies the products or services the company plans to sell, its target market, the gap in the market it is trying to fill, any anticipated expenses and a financial model to operate in a profitable manner. While the primary objective of publicly traded firms is to maximise profits for their shareholders, social and environmental sustainability have recently become a major driver for innovation in companies' business models. Moreover, business models are not only used to provide revenue certainty, but can also tackle specific risks and allocate them in a fair and balanced manner (for instance, between governments and private sector actors for CCUS).

A primary component of a business model is its value proposition, explicitly stating the value and attractiveness of the product or service offered to the customer. Establishing the value of CCUS is crucial in order to be able to establish a functional business model for it. The value of CCUS centres on emissions reduction and/or removals, economic revenues generated from selling the captured $CO_2$, and/or the creation of low-emissions products (e.g. low-emissions cement, low-emissions steel). *

The value proposition of CCUS can change depending on the key drivers behind CCUS business models. A CCUS model focusing on meeting ambitious climate targets will rely on policy and regulation, while a model focusing on economic return will aim to increase revenues and decrease costs. So far, most operating CCUS plants have relied on a CCUS value proposition favouring economic revenues from using or selling $CO_2$ (e.g. for EOR), with a lack of policy and regulation giving meaningful value to emissions reduction.

Each government should assess the role of CCUS technologies within its long-term targets of growth and climate change mitigation in order to clearly establish a CCUS value proposition, and act accordingly. The goal should be to support private investments towards emerging technologies and approaches that provide social goods, and to redirect private capital away from emission-intensive activities towards low-emissions ones. In order for governments to be successful in reaching this goal, they should iterate based on real-world experience with policies as well as learning from other jurisdictions. This requires an understanding of corporate incentives and the types of businesses that policies might successfully attract.

* Note: IEA analyses highlight the stronger need for $CO_2$ storage (compared to the need for $CO_2$ utilisation) but see a role for both routes and for a full portfolio of CCUS technologies in order to meet net zero emission targets globally.

# From full-chain to part-chain model

## Moving away from the full-chain model

With a few exceptions, most commissioned CCUS projects to date have operated on the same business model: they are “full-chain” projects where $CO_2$ is transported from one capture facility to one injection site, typically involving a single project framework. While the full-chain model was a natural model for first-of-a-kind (FOAK) CCUS projects, full-chain projects suffer from high investment, cross-chain risks and liabilities born by a single developer. Breaking-up the CCUS value chain can help mitigate these hurdles as CCUS scales up, while avoiding monopolistic behaviour. We are now seeing this happening, with part-chain projects focused on capture, transport and/or dedicated storage developing in connection to emerging shared infrastructure within CCUS hubs.

Both full-chain and part-chain projects can be developed through a joint venture ownership model, where a new company (a joint venture company, owned by the participating stakeholders) is created for each new project. This is usually the ownership model behind CCUS hubs and clusters, and applies to private as well as public stakeholders. In a joint venture, financial risk is reduced because it is spread across the different partners (e.g. at least two organisations, dealing with $CO_2$ capture and $CO_2$ transport and storage), but co-operation and agreement on where and how other risks are best tackled is essential to guarantee alignment among the various steps of the CCUS chain.

Part-chain projects also come with their own challenges, starting with co-ordination among the various steps of the chain. Emitters are reluctant to invest in capture facilities if they do not have any certainty on where to store the captured $CO_2$ and how to get it there; transport and storage operators seldom advance with their planning unless they manage to secure at least a couple of initial customers. This uncertainty makes financing these projects hard. Moreover, with multiple potential customers looking for a way to deal with their own emissions, there is a need to co-ordinate the technical specifications for transporting and storing $CO_2$ in shared networks.

## New players for new business models

Historically, oil and gas companies have been leaders in CCUS development. They have the experience, subsurface and facilities, project management and financing capabilities to successfully deliver fully integrated CCUS projects and parts of projects. They manage most of the existing $CO_2$ pipelines and all of the dedicated $CO_2$ storage projects in operation. Moreover, they are involved in over half of current operational capture capacity, with ExxonMobil, Chevron, Shell and Occidental together accounting for around 80% of that capacity.

While oil and gas companies remain heavily involved in CCUS projects, and the CCUS portfolio can support the energy transition of producing economies, breaking-up the CCUS value chain into its constituent components is allowing new specialised players to emerge. Over time, a larger role may be possible for heavy industries (steel, chemicals, cement) as well as original equipment manufacturers and service companies. Emerging players who are already involved in recently announced projects include:

- Chemical companies, leveraging their technical know-how to develop proprietary capture technologies, both to reduce emissions from their own facilities and to provide capture solutions to third parties.
- Engineering companies and original equipment manufacturers (OEM) developing proprietary capture solutions, with modular capture skids for third-party emitters, and potentially offering capture-as-a-service (particularly to smaller emitters).

- Infrastructure companies expanding their portfolio to $CO_2$ management, such as gas infrastructure developers who are increasingly involved in building and operating $CO_2$ pipelines, sometimes retrofitting existing gas assets.
- Liquefied natural gas carriers and shipping companies expanding into $CO_2$ shipping.
- New companies focusing exclusively on CCUS.

### Selected examples of CCUS business models

| Business model | Main features | Examples of operational plants and commercially available technologies |
|---|---|---|
| Full-chain model | Single project framework across entire CCUS supply chain: vertical integration model within the same organisation.<br><br>*Advantages*: Fewer synchronisation efforts. This business model allows for greater integration for a company that can invest and operate the entire CCUS industry chain.<br><br>*Challenges*: Complex and therefore limited to companies with the resources to invest and manage; difficult to expand. | Uthmaniyah $CO_2$ EOR Demonstration project (Saudi Arabia, 2015)<br><br>Karamay Dunhua methanol plant (China, 2015)<br><br>Core Energy $CO_2$-EOR South Chester plant (United States, 2003)<br><br>Illinois Industrial Carbon Capture and Storage (United States, 2017)<br><br>MOL Szank field $CO_2$ EOR (Hungary, 1992)<br><br>Sinopec Nanjing Chemical Industries CCUS Cooperation Project (China, 2021)<br><br>CNOOC Enping offshore CCS (China, 2023)<br><br>Petrobras Santos Basin pre-salt oilfield CCS (Brazil, 2013)<br><br>Sleipner (Norway, 1996)<br><br>Snøhvit (Norway, 2008)<br><br>Quest (Canada, 2015)<br><br>Gorgon (Australia, 2019) |
| Self-capture with third-party $CO_2$ offtake | In this model, the (potential) emitter takes care of the capture step, operating the capture unit, and sells the captured $CO_2$, or relies on a third party for $CO_2$ transport and storage.<br><br>*Advantages*: simple approach. The emitter decarbonises its own business while generating revenues at the same time (e.g. by selling low-emissions electricity or products and the captured $CO_2$).<br><br>*Challenges:* risky approach for both parties if they each rely on a single client or supplier. The price for $CO_2$ captured | Coffeyville fertiliser plant (United States, 2013)<br><br>Great Plains Synfuel Plant Weyburn-Midale (United States, 2000)<br><br>Enid fertiliser plant (United States, 1982)<br><br>Arkalon $CO_2$ compression Facility (United States, 2009)<br><br>Bonanza Bioenergy CCUS (United States, 2012)<br><br>Boundary Dam CCS (Canada, 2014)<br><br>China Energy Taizhou power (China, 2023)<br><br>PCS Nitrogen-Geismar plant (United States, 2013) |

| Business model | Main features | Examples of operational plants and commercially available technologies |
|---|---|---|
| | through CCUS applications may not be competitive on an open market. | Lost Cabin Gas Plant (United States, 2013)<br><br>Valero Port Arthur Refinery (United States, 2013)<br><br>Mikawa Power Plant BECCS Fukuoka Prefecture (Japan, 2020)<br><br>NWR $CO_2$ Recovery Unit (Canada, 2020)<br><br>WCS Redwater $CO_2$ Recovery Unit (Canada, 2019)<br><br>Global thermostat headquarters plant (United States, 2023)<br><br>Labarge Shute Creek Gas Processing Plant (United States, 1986)<br><br>China Energy Jinjie power (China, 2021) |
| $CO_2$ transport and/or storage as-a-service | One company (or a consortium of companies, potentially including state-owned enterprises) deals with $CO_2$ captured from various emitters to transport it and store it safely underground. Two companies could be involved, if one deals with $CO_2$ transport and the other with $CO_2$ storage. Given transport and storage infrastructure is a natural monopoly, the ownership model is likely to rely substantially on the government's participation or via a regulated asset base model.<br><br>*Advantages:* if the $CO_2$ is sufficiently priced and a long-term purchasing contract is in place, the $CO_2$ transport and storage operator faces low risks. With state ownership, there is easier access to finance, usually at lower rates than those faced by private organisations when operating alone.<br><br>*Challenges:* long lead time, need to start planning/investing before customers have committed to any purchasing agreement. | Terrell Natural Gas Processing Plant (United States, 1972)<br><br>Abu Dhabi CCS Project (United Arab Emirates, 2016)<br><br>Changling Gas plant /Jilin Oil Field $CO_2$-EOR Full-scale (China, 2018)<br><br>Clive $CO_2$-EOR (Canada, 2020)<br><br>Alberta Carbon Trunk Line (Canada, 2020)<br><br>Cortez Pipeline (United States, 1983) |
| Capture-as-a-service | This business model refers to private organisations specialising in specific part of the CCUS chain related to $CO_2$ capture. They may supply the capture equipment, or just a specific component (e.g. | Just Catch capture system (Aker Carbon Capture)<br><br>CANSOLV capture system (Shell)<br><br>CyclonCC capture system (Carbon Clean) |

| Business model | Main features | Examples of operational plants and commercially available technologies |
| --- | --- | --- |
| | separation columns, $CO_2$ compressors) or consumable ($CO_2$ solvent). The companies offering capture-as-a-service to emitters can either act as project developers (owning and operating the capture unit) or rely on technology licensing.<br><br>*Advantages:* availability of commercial standard solutions as well as more customisable solutions.<br><br>*Challenges:* stable demand for non-CCUS related applications, potential lack of demand for CCUS ones; lack of established supply chains for core components and consumables. | Econoamine FG Plus capture system (Fluor)<br><br>KM CDR Process capture system (MHI)<br><br>Cryocap, Recticap and Rectisol capture systems (Air Liquide)<br><br>VeloxoTherm capture system (Svante)<br><br>Modular carbon capture and storage (MCCS, Entropy)<br><br>Leilac calciner for cement production (LEILAC Group)<br><br>Ortloff $CO_2$ fractionation system, $CO_2$ Polybed PSA system, AmineGuard FS Process, Calidus Burners (Honeywell)<br><br>BrightLoop, SolveBright, and OxyBright (Babcock & Wilcox)<br><br>CapsolEoP and CAPSOLGT (Capsol Technologies)<br><br>LCDesign, Delta Reclaimer, Deltasolv (Delta Cleantech)<br><br>Belco and Dynawave wet scrubbing system (Elessent Clean Technologies)<br><br>HISORP CC, HISELECT, and Rectisol wash unit (Linde)<br><br>Toshiba post-combustion capture technology (Toshiba)<br><br>Orca (Climeworks) |

Sources: IEA (2023), CCUS Projects Database; Global CCS Institute (2023).

### Selected CCUS hubs approaches

Various approaches for the hub and cluster model are possible:

- **Hub developers can provide $CO_2$ transport and storage services**. This is the case for the Northern Lights transport and storage hub in Norway, a joint venture between Equinor, Shell and Total Energies (with strong support from the Norwegian Government, around 80% of the initial capital investment). The project is developing infrastructure to transport $CO_2$ from capture sites by ship to a receiving terminal in western Norway for intermediate storage, before being transported by pipeline for permanent storage in an offshore reservoir. Another example is the Alberta Carbon Trunk Line (ACTL), operational since 2020 in Alberta (Canada). The ACTL includes participation from multiple partners (North West Redwater Partnership Sturgeon Refinery and Nutrien's Redwater Fertilizer Facility) to capture industrial emissions and deliver $CO_2$ through a pipeline (owned by Wolf Midstream) to mature oil and gas reservoirs (owned by Enhance Energy) for use in EOR and permanent storage in Central Alberta.

- **Some hubs are built by companies intending to initially deal with their own emissions**, around an 'anchor project', but with the perspective of opening up to other emitters. In Italy, the Ravenna Hub, developed by Eni and Snam, plans to initially capture and store offshore around 25 000 t $CO_2$/yr by 2024 from Eni's natural gas treatment plant. In its second phase, the project will increase capacity to around 4 Mt $CO_2$/yr by 2030, with most of the capacity coming from industrial emitters in the north of Italy connected to the hub by a pipeline network developed by Snam.
- In China, the Junggar Basin Hub, led by China National Petroleum Corporation (CNPC), plans to store $CO_2$ captured initially from CNPC operations, and later from hydrogen, cement and steel, as well as power generation in the region.
- **The hub can be supported by a partnership aiming to deploy strategic infrastructure**. This is the case of the Porthos (Port of Rotterdam $CO_2$ Transport Hub and Offshore Storage) Hub in the Netherlands, aiming to store $CO_2$ emissions from the port in a depleted offshore gas field. Porthos is a partnership between the Port of Rotterdam Authority, Gasunie (one of the main Dutch Transmission System Operators [TSOs]) and Energie Beheer Nederland (EBN) (a Dutch public energy company). The Port of Rotterdam Authority will be focusing on the local situation and market, Gasunie can offer extensive experience with gas infrastructure and transport, and EBN will be sharing its expertise in subsurface reservoirs and offshore infrastructure.
- **The hub can also be initiated by a consortium of industrial companies**. In Belgium, the Antwerp@C $CO_2$ export hub involves the Port of Antwerp alongside seven industrial partners* from the energy and chemical sectors. The hub aims to develop a world-scale open-access modular infrastructure for the transport, liquefaction, and export of $CO_2$ captured by industries in the Antwerp port area, to support the goal of reducing its $CO_2$ emissions by 50% by 2030. The export terminal will have a capacity of around 2.5 Mt $CO_2$, with plans to increase to 10 Mt $CO_2$ by 2030. In Canada, industrial companies are also partnering with indigenous communities to advance hub solutions. For example, the proposed Open Access Wabamun Carbon Hub west of Edmonton, Alberta, which will have the potential to sequester nearly 4 Mt $CO_2$ annually, will be co-developed and co-owned with local indigenous partners. In the United States, a number of industrial consortiums have applied for funding for up to four regional direct air capture (DAC) hubs. The hubs will facilitate the deployment of DAC projects, will demonstrate the capture, processing, delivery and sequestration or end-use of captured carbon, and

could even be developed into a regional or inter-regional carbon network to facilitate sequestration or carbon utilisation.

- **The hub can be supported by a specialised infrastructure company**, such as a TSO. That is the case for a few European TSOs, including Snam in Italy (Ravenna Hub), Gasunie in the Netherlands (Porthos and Aramis) and Fluxys in Belgium (Ghent Carbon Hub and Antwerp@C).

* Note: Air Liquide, BASF, Borealis, ExxonMobil, INEOS, Fluxys and Total Energies.

# Possible revenue streams

Market-led revenue streams can supplement policy-related revenue streams. Revenue stream options that are not strictly related to policy include using the captured $CO_2$ on-site or selling it to a third party for utilisation (for $CO_2$-based products such as fuels, chemicals or building materials); selling low-emissions products (low-emissions steel or low-emissions cement); and storing the captured $CO_2$, for instance to provide a $CO_2$ removal service.

## Direct use of $CO_2$

Carbon capture and utilisation (CCU) refers to a range of applications through which $CO_2$ is captured and used either directly (i.e. not chemically altered) or indirectly (i.e. transformed) in various products. Climate benefits associated with a given $CO_2$ use depend on the source of the $CO_2$ (from natural source reservoirs, fossil, biogenic or air-captured), the product or service the $CO_2$-based product is displacing, the carbon intensity of the energy used for the conversion process, and how long the $CO_2$ is retained in the product. While some $CO_2$ use could bring substantial climate benefits, the relatively limited market size for these applications means dedicated storage should remain the primary focus of CCUS deployment. However, support for RD&D can play a key role in the deployment of promising $CO_2$-derived products and services that are scalable and have good prospects to become competitive over time. CCU also promotes the development of capture technologies and infrastructure deployment. Finally, CCU has the potential to contribute to a circular carbon economy (where the maximum value of resources is used before disposing of them) and to help create a market for carbon capture technologies and therefore bring their price down.

The main direct use of $CO_2$ today is for EOR. In addition, $CO_2$ can be used as a working fluid for other underground applications, including enhanced gas recovery (EGR) and enhanced water recovery (EWR). The primary objective of $CO_2$ injection in these applications is to enhance extraction. While most of the $CO_2$ injected for EOR is retained in the reservoir over the life of the project, additional monitoring and verification is required to confirm that the $CO_2$ has been permanently stored. $CO_2$ EOR has been the most effective incentive for CCUS so far, with around three-quarters of current operating capture projects using or selling the captured $CO_2$ for EOR. Moreover, EOR subsurface know-how is well suited to geological storage development. As an example, in Canada, EOR operators like Enhance Energy and Whitecap Resources possess $CO_2$ injection and storage expertise that can be applied to the development of dedicated geological storage hubs. Enhance Energy is using its EOR experience from the ACTL to develop a storage hub in Central Alberta, while Whitecap is leveraging its EOR experience at Weyburn to develop a storage hub in south-east Saskatchewan.

However, in the Net Zero Emissions by 2050 Scenario (NZE Scenario), reliance on fossil fuels such as oil and gas decreases over time towards mid-century, with dedicated $CO_2$ storage becoming the long-term solution for captured $CO_2$. While EOR helped spark the industry, experience has shown that it may not be a reliable revenue stream for CCUS projects, and in the long run it may not align with policy goals. In fact, based on the CCUS projects announced in the past few years, companies are increasingly shifting away from EOR.

**Is EOR a good revenue stream for CCUS?**

There is no official public record of $CO_2$ prices paid by oil and gas companies for EOR operations, but a rough benchmark is around USD 30/t $CO_2$ when the oil price is around USD 70 per barrel, with the two prices closely correlated. Such a price is high enough to cover CCUS costs only for limited applications producing very concentrated streams of $CO_2$, such as natural gas processing, ammonia, and some fuels such as bioethanol (see Chapter 4). However, oil prices are subject to substantial market volatility, with CCUS projects suspending operation because selling $CO_2$ was no longer profitable. As an example, operation of the Petra Nova CCUS plant was suspended in 2020 when $CO_2$ capture ceased to be profitable due to low oil prices. Another example is the Shute Creek CCUS plant: over its operational lifetime to date, the plant (commissioned in 1986 to capture $CO_2$ during natural gas refining) captured only around 34% of its operational capture capacity (around 120 Mt $CO_2$ cumulatively). The captured $CO_2$ was then mostly vented (50%) or sold for EOR injection (47%). EOR-related revenues alone are not enough for maximising capture and storage as a public policy goal. CCUS projects should therefore be able to rely on more stable revenue streams that are compatible with net zero goals (supported and/or enabled by policies), rather than on revenues from selling oil, which has proven to be a risky revenue stream in the past.

## Low-emissions products

Emitters have the option to sell premium, low-emissions products for a premium price. Low-emissions products include those that have been produced with very low emission intensities, such as low-emissions steel and cement (see Chapter 4). They can also include indirect use of $CO_2$ in products,[15] such as synthetic fuels, chemicals or building aggregates, if produced under the right conditions (e.g. using low-emissions energy for $CO_2$ conversion).

Some of these applications are already in regulated markets, such as under the Low Carbon Fuel Standard regulations, and efforts are underway to protect these premium products against emission-intensive and cheaper imported goods (see Chapter 5).

The First Movers Coalition (launched at COP 26 in November 2021 and led by the World Economic Forum) is an example of a privately-led initiative aiming at aggregating demand for low-emissions products such as aluminium, cement and steel. Another example is the Industrial Deep Decarbonisation Initiative (co-ordinated by UNIDO and designed to stimulate global demand for low-emissions industrial materials).

## Carbon markets

$CO_2$ storage can shift from a cost to a source of revenue in those regions and countries where there is a carbon pricing system in place. If the carbon price stays as high as recently seen in some markets such as the European ETS (around USD 85/t $CO_2$), the full cost of capturing, transporting and storing $CO_2$ can be compensated by the carbon price only for selected applications such as natural gas processing, bioethanol production and hydrogen production (see Chapter 4).

In the absence of a compliance market, emitters can sell carbon credits in the voluntary carbon markets based on certified emissions reduced or removed through CCUS. Voluntary carbon markets (VCMs) are expanding substantially, stimulated by the demand generated by growing corporate net zero commitments. The carbon credit price on those markets can be particularly advantageous for $CO_2$ removals or CDR (on average, around USD 300 per tonne of $CO_2$ captured and stored via bioenergy with carbon capture and storage [BECCS], and around USD 720/t $CO_2$ via DAC). Removals are currently supported almost exclusively through voluntary carbon markets, and initiatives such as CCS+ (under development) or the Australian Carbon Credit Units (ACCU, now in place) are developing the first methodologies, but public initiatives are also getting underway,

[15] Emissions accounting needs to rely on life cycle assessment methodologies for $CO_2$ use not resulting in permanent storage.

such as in the United Kingdom, and the European Union, with its Carbon Removal Certification Framework (see Chapter 5).

**Revenue streams by Technology Readiness Level (TRL)**

Different business models are needed for different stages of technology and commercial development. This is true now for CCUS, but was also true in the past for other network industries such as natural gas and water. In addition, different types of CCUS (especially CCU for chemicals) have different revenue expectations at varying TRLs as the size of the test facility at each stage determines how much capital is put at risk. Depending on the model, the government's level of intervention and risk will vary.

- **Prototype stage (TRL 4-6)**: at this stage, there is a strong need for the government to intervene due to the lack of an established market. In this model, the government takes on much of the investment risks and operating costs, contracting planning, development and operations to state-owned or private entities. This was the case for the first phase of the Northern Lights project. The private sector may also provide some support, in the form of philanthropic funding or equity investment.
- **Demonstration stage (TRL 7-8)**: at this level, risks are shared between the public and private sectors, and a hybrid model comprising government intervention as well as market competition can be applied. While important, the government's role is narrowed, and limited mostly to supporting $CO_2$ infrastructure. For example, a regulated entity could be responsible for taking the captured $CO_2$ from emitters and developing the supporting transport and storage infrastructure. Some examples of this approach include the East Coast Cluster in the United Kingdom (with $CO_2$ infrastructure operated by the Northern Endurance Partnership) and the Porthos project in the Netherlands. For both projects, the $CO_2$ transport and storage operator is supported by the government and is able to charge a fee to take on the captured $CO_2$.
- **Mature technologies (TRL 9-11)**: the private sector takes on most of the risk in a mature industry, without direct government intervention applied to the market itself. This model applies mostly to liberalised economies (it may struggle to take off in centrally controlled economies) and is economically suitable where both market incentives and policy regulations are sufficient to make a profit out of the business itself. The private sector is free to decide how its businesses will be structured, whether to invest in oversized transport and storage capacity, and how to allocate risk and return. Currently this model does not apply to CCUS applications beyond natural gas processing, EOR and ammonia. It is important to note that even in a mature market model, there is still a need for a strong regulatory environment to ensure the safe and secure storage of $CO_2$.

# Chapter 4: Challenges for future deployment

While many clean energy technologies face deployment hurdles, carbon capture, utilisation, and storage (CCUS) projects face specific challenges related to the inherently site-tailored nature of the technology – technologies are usually individually designed and manufactured to fit specific processes – and the need to deploy large-scale infrastructure. In addition, the value proposition for CCUS is solely based on its $CO_2$ reductions, in contrast to other clean energy technologies, such as solar PV and wind, whose value proposition also comes from electricity generated.

Economic viability remains a significant hurdle, as costs associated with CCUS technologies can be prohibitively high compared to unabated technologies. Long lead times for project development and implementation further impede progress, particularly with regards to $CO_2$ storage development. As new business models develop, project complexities also change, requiring greater co-ordination across the value chain, mitigation of counter-party risks and allocation of long-term liability, as well as the access to and management of shared, cross-border $CO_2$ transport and storage infrastructure. Finally, while some of the CCUS technologies have been in use for decades, there is a need for continuous innovation to reduce the energy penalty and costs for CCUS applications that are critical to net zero.

An understanding of these challenges will be necessary in order to best design policies to support the timely roll-out of CCUS in different sectors of the economy.

## Economic viability

### Levelling the playing-field with unabated facilities

Facilities equipped with CCUS are more costly to build and operate than their unabated counterparts. This is because they require additional equipment to capture $CO_2$ and more energy, material (e.g. solvent) and water per unit of final product (e.g. electricity or materials such as cement or steel). Carbon pricing, whether through carbon taxes or emission trading systems, can help make CCUS more economically attractive by imposing a cost or a cap on emitting $CO_2$ into the atmosphere. However, if the carbon price is too low or the cap is too high, these measures can be ineffective or even counterproductive.

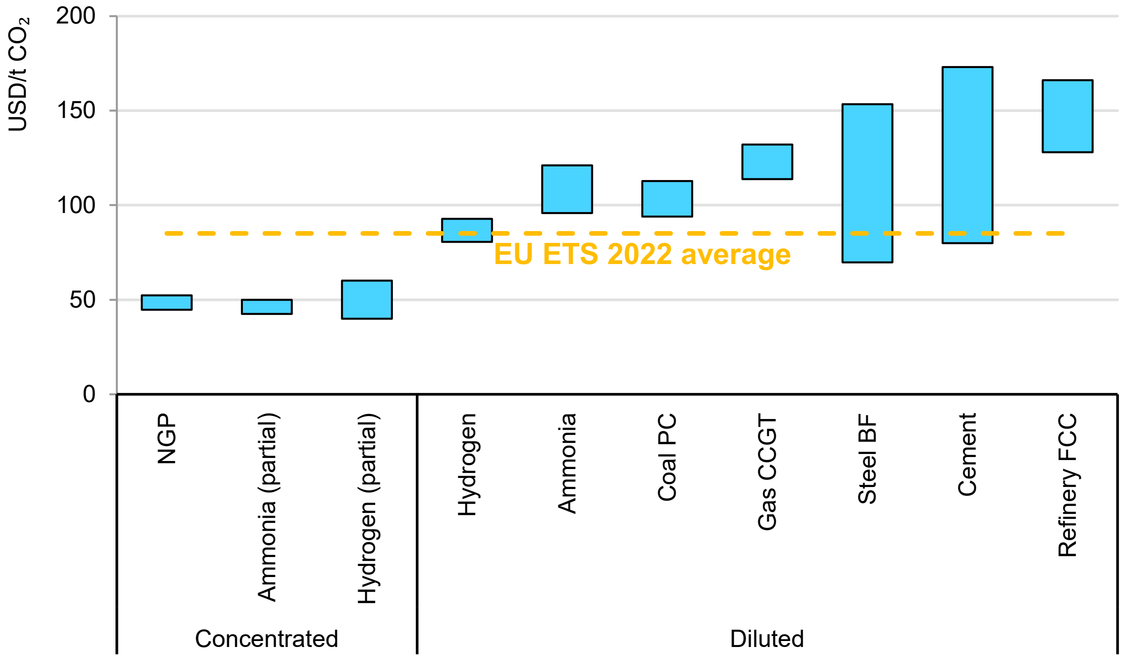
The level of carbon pricing required for facilities equipped with CCUS to breakeven with their unabated counterparts depends on the levelised cost of carbon avoided[16] by CCUS in a particular sector. Our analysis shows that carbon prices between USD 40-60/t $CO_2$ are required for CCUS-based routes to breakeven with unabated routes for high-concentration applications, and between USD 80-170/t $CO_2$ for diluted applications. $CO_2$ prices around USD 85/t $CO_2$, as observed in 2022 in the European Union (annual average), while promising, would only be sufficient to incentivise concentrated applications and dilute applications in optimistic cases. The variability and unpredictability of carbon pricing also creates uncertainty for investors and project developers, making it challenging to secure funding and plan for the long term.

Additionally, most CCUS applications which are particularly important for the net zero transition (including cement, steel, power, hydrogen, $CO_2$ removal) are at first- or second-of-a-kind level of deployment. While a carbon price could support nth-of-a-kind plants, additional policy measures for targeted support are needed in the short to medium term to help these early plants get off the ground.

In the United States, the recent update of the 45Q tax credit, which provides USD 85/t $CO_2$ captured for dedicated storage and USD 60/t $CO_2$ used in industrial applications and enhanced oil recovery (EOR), is improving the attractiveness of CCUS, but remains insufficient for most applications.

[16] See Annex B for more information on CCUS cost metrics definitions. Here the levelised cost of $CO_2$ avoided includes a $CO_2$ transport and storage cost of USD 30 per tonne of $CO_2$.

**Levelised cost of $CO_2$ avoided between CCUS and unabated route across sectors**






Notes: BF = blast furnace; CCGT = combined cycle gas turbine; FCC = fluid catalytic cracker; NGP = natural gas processing; PC = pulverised combustion. Cost of electricity: USD 32-116/MWh; cost of fuel (USD/GJ): 4-14 (natural gas), 2-7 (coal), 7-9 (biomass); plant financial lifetime (years): 40 (coal and biomass thermal plants), 35 (gas CCGT), 25 (all other plants); discount rate: 8%; capacity factor: 85% (power plants), 95% (all other plants); capture rates: 60% (partial hydrogen, ammonia), 90% (all), 93% (hydrogen, ammonia); $CO_2$ transport and storage: USD 30/t $CO_2$. No carbon price. Capture rates are for the overall plant (power, hydrogen, cement), or for the flue gas when a specific unit is specified (steel blast furnace, refinery fluid catalytic cracker). For hydrogen, DAC, fuel transformation and industry applications, heat is assumed to be provided by a natural gas-fuelled auxiliary boiler, and electricity from the grid.

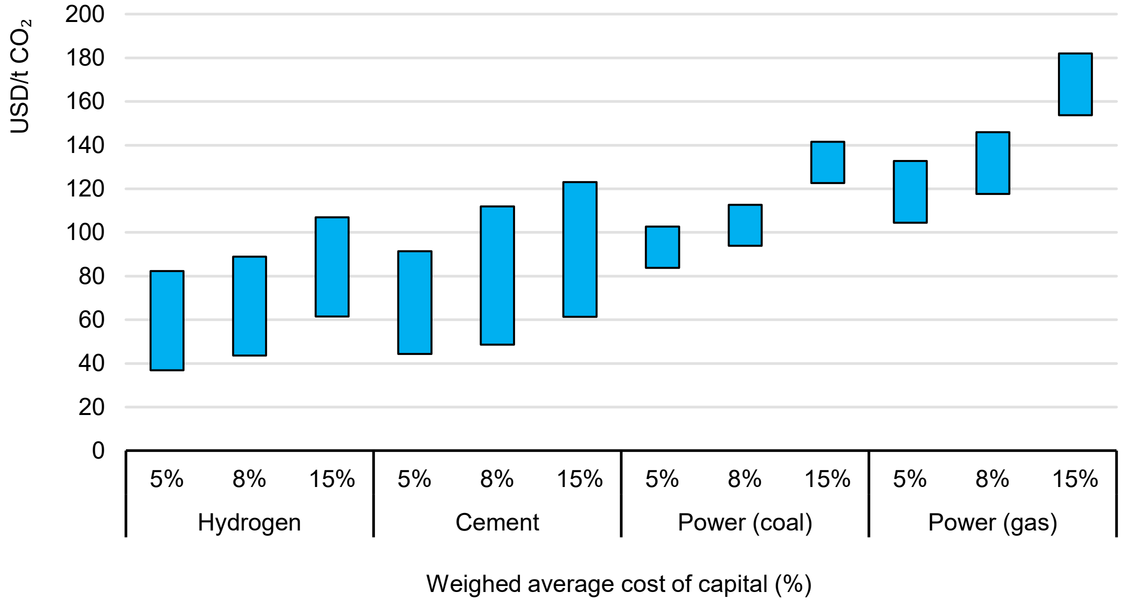
## High up-front investment

One of the most significant economic challenges of CCUS is the high upfront capital costs associated with building carbon capture facilities and transport, and storage infrastructure. CCUS can increase capital costs by 40-75% relative to unabated facilities in coal-based power generation, 95-110% for gas CCGTs and 75-100% for biomass-based power generation. In cement production, capital costs can increase by 110-125% with CCUS, and by 30-45% in steel production.

High up-front project costs mean that companies potentially need to take on large amounts of debt, which poses significant hurdles. Potential solutions include grants, which can help lower the initial amount of debt a project takes on, and operational subsidies that can help companies secure investment through loans, since the subsidies provide a reliable revenue stream to pay down the debt.

CCUS projects also have a different risk profile to unabated facilities, owing to higher uncertainties around costs and techno-economic performance of first-of-a-kind facilities, and long-term liabilities tied to dedicated $CO_2$ storage. A higher risk profile can increase the cost of capital for project developers. Given the large contribution of capital costs to the overall levelised costs of capture, increasing the cost of capital from around 5% to 15% can increase levelised costs of capture by 30-65% in hydrogen, cement, and power generation. This can be particularly challenging and act as a deterrent to investments for emerging economies, which are characterised by higher costs of capital than advanced economies for large-scale energy projects in general.

**Impact of cost of capital on levelised cost of capture for selected sectors**






Notes: CCGT = combined cycle gas turbine; PC = pulverised combustion. Cost of electricity: USD 32-116/MWh; cost of fuel: USD 4-14/GJ (natural gas), USD 2-7/GJ (coal), plant lifetime (years): 40 (power plant), 25 (hydrogen, cement); discount rate: 8%; capacity factor: 85% (power), 95% (cement, hydrogen); plant level capture rates: 90 (all) – 93% (hydrogen).

## Competitiveness with alternative low-emissions technologies

The ability of CCUS to capture demand for high-cost but low-emissions energy and products hinges on its competitiveness with alternative low-emissions technologies in a given sector and region. For certain applications such as power generation, steel manufacturing and hydrogen production, multiple decarbonisation technologies exist. The role of CCUS is therefore likely to be limited to regional contexts where the deployment of alternative solutions is constrained, for example due to low availability of low-emissions electricity or hydrogen. However, for other applications such as cement production and carbon dioxide removal, CCUS is one of very few – if not the only – technology solution that can deliver emissions reduction and permanent removal at scale.

Policy initiatives to increase the demand for high-cost but low-emissions energy and products can help bridge the economic gap between low-emissions technologies and their unabated counterparts. High capture (90% and beyond) (see Box ''Can high plant capture rates be achieved?'') and low upstream emissions associated with fossil fuel production, are particularly essential for CCUS routes to be considered low-emissions and be comparable with alternative low-emissions technologies.

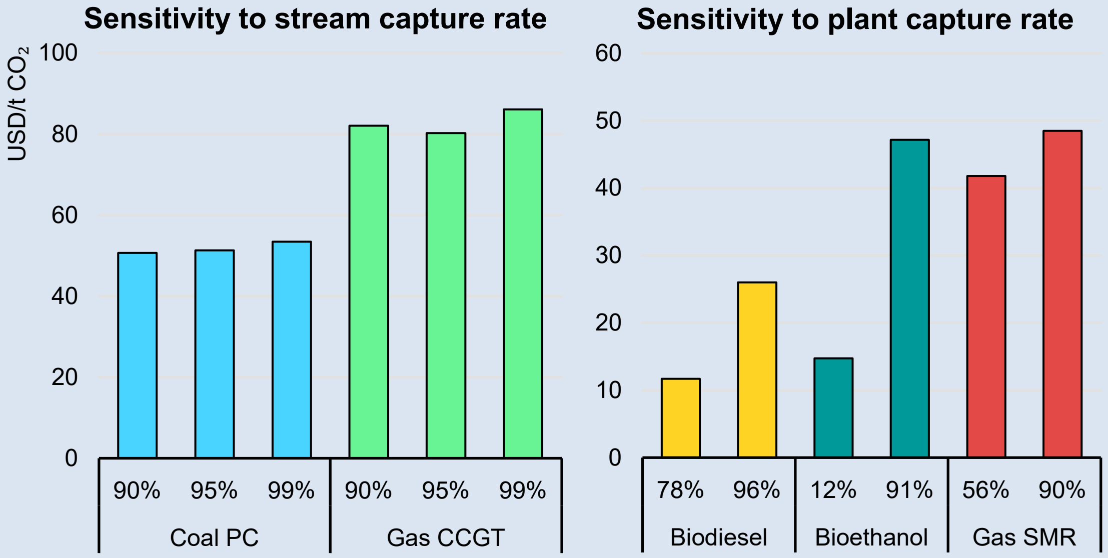
**Can high plant capture rates be achieved?**

- In recent years there have been numerous discussions at the international level about reducing the share of fossil fuels in the global energy mix in order to mitigate climate change. During COP 26 in 2021, participating countries agreed to a provision calling for a phase-down of unabated coal power and a phase-out of "inefficient" fossil fuel subsidies. The same language was maintained in the COP 27 cover decision the following year. Central in this discussion is the terminology around abated versus unabated fossil fuels. While the general understanding is that unabated fossil fuel use refers to ''consumption of fossil fuels in facilities without CCUS'', not all CCUS facilities are designed to capture the same amount of emissions. Ahead of COP 28 (taking place in the United Arab Emirates in late 2023), it is important to highlight that high capture rates (i.e. above 90%) are essential in order to minimise residual emissions to the atmosphere, and for CCUS to play a role in the transition to a net zero energy system.
- Plant capture rates depend on the share of plant emissions which are equipped with capture (particularly when plant emissions originate from multiple sources, for example in a steel plant, which can require several capture units), and on the capture rate of the capture system(s) used on each single stream (i.e. stream capture rate).
- For the latter, CCUS-equipped power and industrial plants operating today are usually designed to operate with a 90% capture rate on each flue gas stream. While there are no technical barriers to increasing stream capture rates beyond 90% for the most mature capture technologies (e.g. chemical absorption), stream capture rates of 98% or higher require larger equipment, more process steps and higher energy consumption. Modelling results based on chemical absorption systems applied to power generation show that the levelised cost of capture does not necessarily increase when increasing capture rates from 90% to 95%, and only marginally increases at 99% capture rates (as the greater amount of $CO_2$ captured can compensate increases in capital and operating costs). In addition, advanced capture technologies including chemical absorption with advanced solvents, oxy-combustion,

membranes and chemical looping, and supercritical $CO_2$ cycles could reach higher stream capture rates and lower energy penalties.

- For facilities with multiple emissions sources, such as steel mills, biorefineries, or hydrogen plants, plant capture rates and associated costs depend on which stream(s) $CO_2$ is captured from and/or the number of capture units. For example, most operating steam methane reforming (SMR) facilities today operate at partial plant capture: only the $CO_2$ in the concentrated shifted syngas is captured, and not the diluted $CO_2$ resulting from fuel combustion from the reformer furnace. This typically results in plant capture rates between 40% and 60%, while plant capture rates of 90% and beyond could be achieved with a capture system that combines both concentrated and diluted streams, but with a significant increase in capture costs. To date, no operational plant has achieved these levels of capture, but two hydrogen plants targeting 90-95% capture are currently under construction in North America. Similar effects can also be observed in biodiesel and bioethanol plants.

**Levelised cost of capture for different stream capture rates in coal and gas power generation (left) and plant capture rates in biodiesel, bioethanol and gas SMR (right)**






Notes: CCGT = combined cycle gas turbine; SMR = steam methane reforming for hydrogen production, PC = pulverised combustion.

Sources: IEA analysis based on NETL (2022), NETL (2022), IEAGHG (2019), IEAGHG (2021), IEAGHG (2017).

## Industry

The industry sector was directly responsible for emitting 9 Gt of $CO_2$ in 2022, accounting for a quarter of global energy system $CO_2$ emissions. The most emission-intensive industrial sectors are the so-called "heavy industries", and include iron and steel, cement, chemicals, aluminium and pulp and paper. CCUS can be integrated into most industrial applications, to capture both combustion emissions (from fuel combustion for heat and electricity needs) and process emissions (from chemical reactions producing $CO_2$ as a by-product).

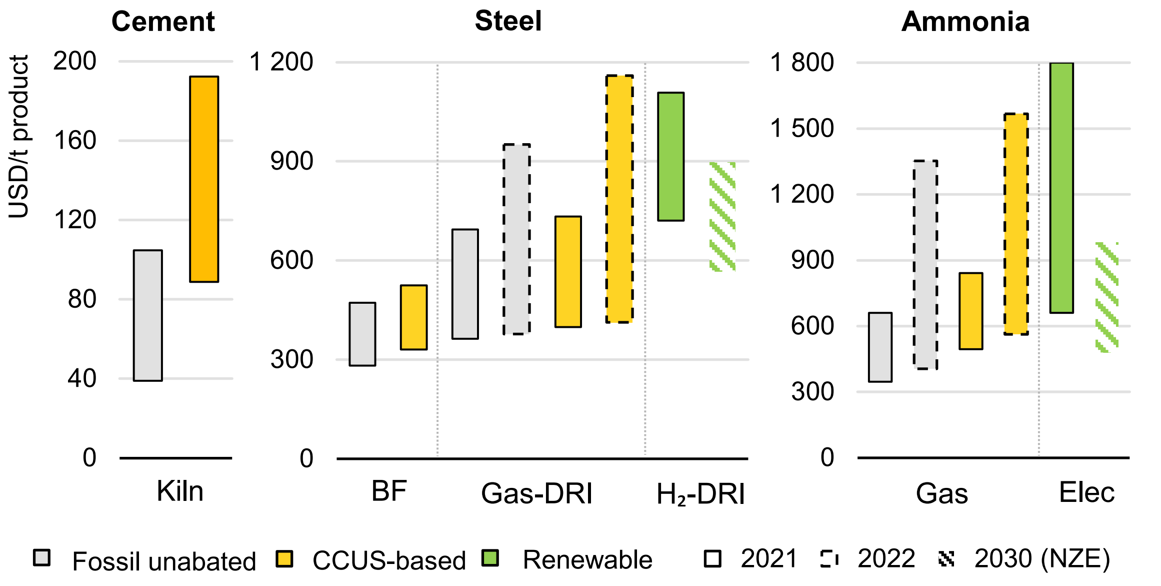
In iron and steel, the main routes to decarbonise production are hydrogen use as a reducing agent and CCUS. Other solutions such as electrification and bioenergy fuel switching can also provide cost-effective carbon reductions, but face technical (for example, electrification of high-temperature heat) or sustainability (sustainable bioenergy supply) constraints. Overall, CCUS can provide cost-effective decarbonisation when the hydrogen route is constrained or more costly due to low availability of renewable electricity, or in regions with secure and low-cost gas supply and access to $CO_2$ storage. Depending on the steel production process, commodity prices and hydrogen production costs, CCUS can increase steel production costs by 10-20%, while the hydrogen route increases costs by 20-25%.

CCUS is also a key technology for the decarbonisation of primary chemicals such as ammonia, methanol and high value chemicals (HVC).[17] By 2050, more than half of production of primary chemicals is equipped with CCUS in the Net Zero Emissions by 2050 Scenario (NZE Scenario). In ammonia production, the main decarbonisation alternatives to unabated gas-based production are CCUS and electrolysis. CCUS can be a cost-competitive solution in the nearer term, as well as in regions with low availability of renewable electricity: ammonia production costs increase by 10-20% with CCUS, while they increase by 40-50% with electrolysis, with decreasing costs of electrolysers. As electrolyser costs come down and renewable electricity prices decrease, electrolysis is expected to become the dominant route globally for ammonia production, while CCUS is expected to play a role in regions with secure and low-cost supply of natural gas and access to $CO_2$ storage.

In cement, even though integrating CCUS to cement kilns can increase levelised cement production costs by 60-130%, CCUS is currently the only technically available solution to address process emissions and achieve near zero emissions in the sector. Other solutions such as the use of alternative raw materials may enable reaching near zero emissions, but are currently at considerably earlier stages of development. In the NZE Scenario, around half of cumulative emissions reductions to 2050 in the cement sector are achieved through CCUS.

[17] High-value chemicals typically include ethylene, propylene, benzene, toluene and mixed xylenes.

**Levelised cost of products for different industries and production routes**






Notes: CCUS = carbon capture, utilisation and storage; BF-BOF = blast furnace basic oxygen furnace; Gas-DRI = natural gas-based direct reduced iron/electric arc furnace (EAF) route; $H_2$-DRI = 100% electrolytic hydrogen-based; Gas = steam methane reforming to hydrogen combined with ammonia synthesis; Elec = renewable-based electrolysis combined with ammonia synthesis; NZE = IEA Net Zero Emissions by 2050 Scenario. Cost of electricity: USD 32-116/MWh; cost of fuel: USD 4-14/GJ (natural gas), USD 3-7/GJ (coal), USD 7-9/GJ (biomass); plant financial lifetime: 25 years; discount rate: 8%; capacity factor: 95%; capture rates: 90% for cement (plant level), 90% for steel (stream capture rate), 93% for ammonia (plant level). $CO_2$ transport and storage: USD 30 per tonne of $CO_2$. 2030 values as projected in the NZE Scenario.

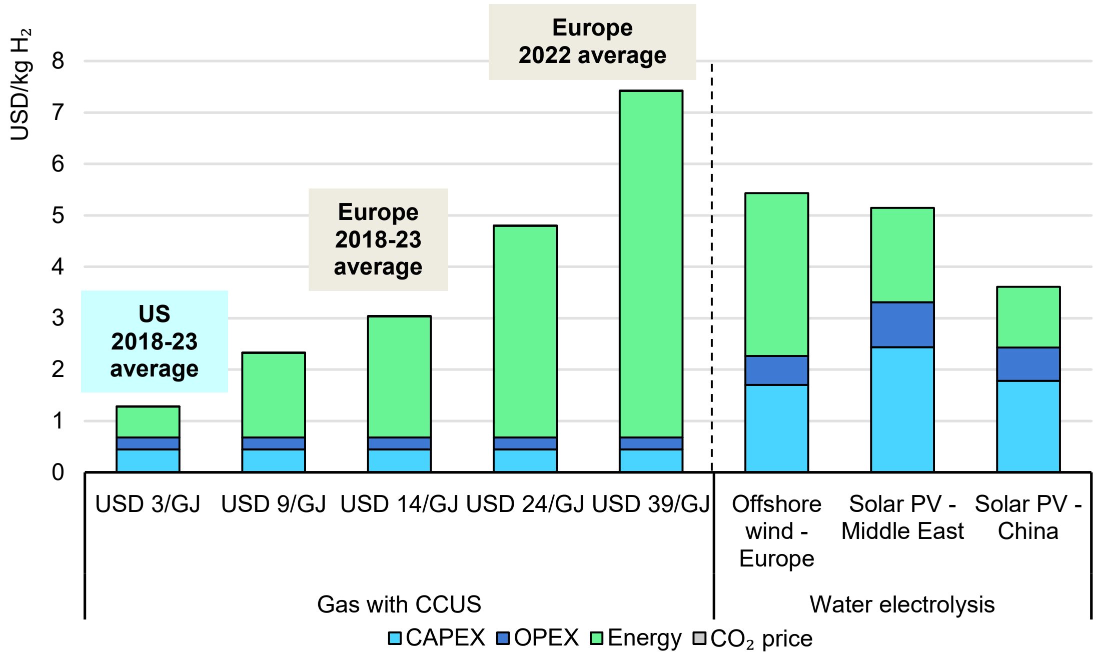
## Hydrogen production

In hydrogen production, the competitiveness of CCUS-based routes with water electrolysis is highly dependent on fuel prices, the price and availability of low-emissions electricity, and potential improvements in electrolyser capital costs and efficiency over time.

Production costs of electrolytic hydrogen based on renewable electricity can be currently assessed between USD 3.6 and 5.4/kg $H_2$ in favourable regions with high availability of renewable electricity, depending on the source of electricity. At natural gas prices below USD 14/GJ (average gas price in Europe in the 2018-23 period), gas-based hydrogen production equipped with CCUS is more economically attractive than renewable electrolytic hydrogen for the best available technologies, with a strike price around USD 26/GJ for electrolytic hydrogen to be competitive in Europe. At prices of USD 40/GJ (average gas price in Europe in 2022), the costs of producing hydrogen with natural gas can be twice as high as the cost of electrolytic hydrogen in favourable regions.

With the cost of renewable electricity and electrolysers expected to fall, electrolytic hydrogen is expected to be increasingly competitive with gas-CCUS production, with gas-CCUS playing a major role only in regions with lower availability of renewable electricity, secure low-cost natural gas supply, and access to $CO_2$ storage. In the NZE Scenario, fossil-based hydrogen production with CCUS makes up around 20% of total hydrogen production in 2050, while electrolysis makes up the remainder.

**Levelised cost of hydrogen production for different regions and gas prices, 2022**





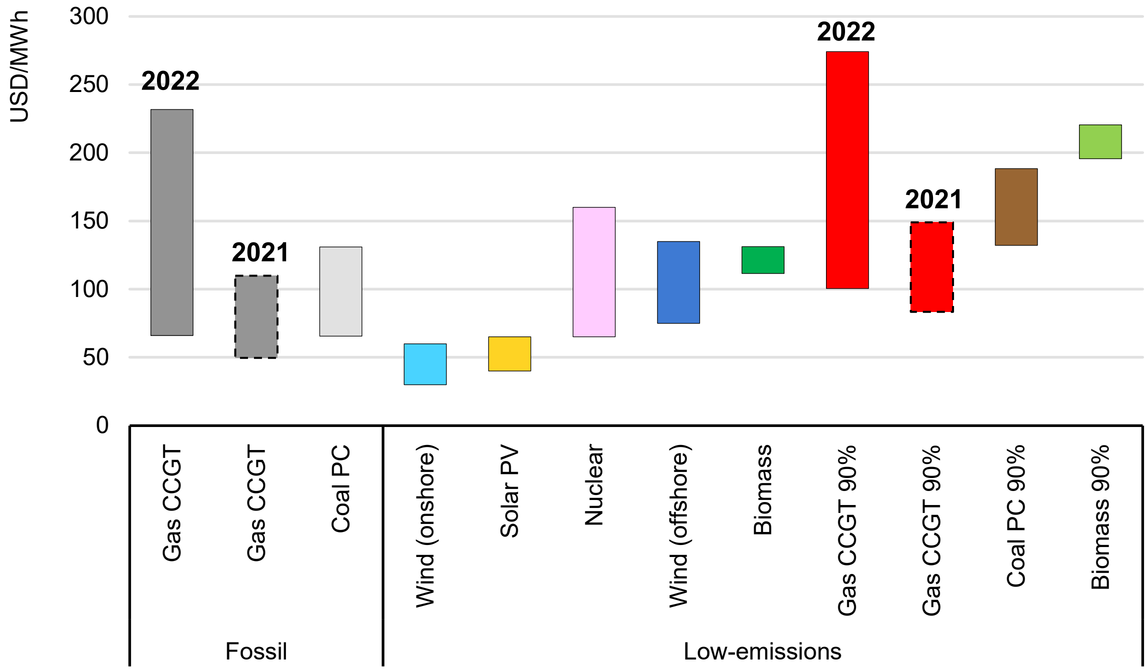

Notes: US = United States; PV = photovoltaics; Gas with CCUS = steam methane reforming with carbon capture, and storage. Main assumptions: CAPEX: USD 1 440/kW (gas-CCUS), USD 1 650-2 530/kW (electrolyser); fixed OPEX: 4% (gas-CCUS), 3% (electrolyser); efficiency (% LHV): 69% (gas-CCUS), electricity price: USD 60/MWh (offshore wind Europe), USD 36/MWh (solar PV Middle East), USD 23/MWh (solar PV China); capacity factor: 95% (gas-CCUS); 42% (offshore wind Europe), 33% (solar PV Middle East); 29% (solar PV China); discount rate/cost of capital: 8%; lifetime: 25 years; overall plant capture rate: 93%; $CO_2$ transport and storage: USD 30 per tonne of $CO_2$. Detailed assumptions will be made available in a forthcoming Annex of IEA (2023).

Sources: IEA analysis based on data from McKinsey & Company and The Hydrogen Council; NETL (2022); IEAGHG (2017).

## Power generation

In power, the value proposition of CCUS for emissions reduction is generally weaker than in other sectors, given the availability of low-cost and low-emissions alternatives such as renewable-based routes. In the NZE Scenario, only around 2% of total electricity generation is supplied by fossil power plants equipped with CCUS in 2050. Depending on coal prices and availability of renewable resources, the levelised cost of electricity (LCOE) of coal plants equipped with CCUS can be 3-3.5 times higher than that of electricity generated by utility-scale solar PV, and 3-4.5 times higher than onshore wind. Depending on gas prices, that of gas plants equipped with CCUS can be 1.5-3.5 higher than solar PV, and 1.5-4 times that of wind.

**Levelised cost of electricity of selected technologies, 2022**






Notes: CCGT = combined cycle gas turbine; PC = pulverised combustion; PV = photovoltaic. Coal includes both ultra-supercritical steam cycle and integrated combined cycles. Main assumptions: CAPEX (USD/kW): 2 630-5 320 (coal), 4 330-7 600 (coal 90%), 1 160 (gas CCGT), 2 280 (gas CCGT 90%), 3 730 (biomass), 6 580 (biomass 90%), 1 100-1 750 (wind onshore), 2 820-4 060 (wind offshore), 640-1 120 (solar PV), 2 800-6 600 (nuclear); efficiency (% LHV): 42-43% (coal), 60% (gas CCGT), 43% (biomass), 33-34% (coal 90%), 52% (gas CCGT 90%), 34% (biomass 90%); load factors: 85% (thermal power plants), 26-42% (wind onshore), 32-50% (wind offshore), 13-21% (solar PV); fuel prices (USD/GJ): 2-7 (coal), 4-14 (gas 2021), 7-32 (gas 2022), 7-9 (biomass); capture rates: 90%; $CO_2$ transport and storage (USD/t $CO_2$): 30; $CO_2$ price (USD/t $CO_2$): 0-65; plant lifetime (years): 40 (coal, biomass, nuclear), 35 (gas CCGT), 25 (renewables); discount rate/cost of capital: 8%.

Sources: IEA (2023); IEAGHG (2019); NETL (2022).

However, CCUS still has potential use cases in the power sector for two main reasons. First, CCUS can avoid the early retirement of young fossil assets and thereby help project developers to recoup investment, which is important for ensuring a smooth transition, particularly in emerging economies characterised by a young industrial and power fleet. In Asia, for instance, the average age of coal plants is 14 years, and more continue to be built.

Secondly, the LCOE metric only provides part of the picture, since it compares the relative cost-effectiveness of technologies operating independently, but does not capture the value of individual power generation technologies operating dynamically as part of a power system, particularly with regards to ensuring grid stability and flexibility. Power plants equipped with CCUS can provide firm low-emissions dispatchable generation, which can reduce the risk of a system's failure, and potentially increase the amount of renewable electricity which can be integrated in the system overall. Power decarbonisation policies which account for this flexibility and capacity value of power generation assets can support CCUS deployment in this sector.

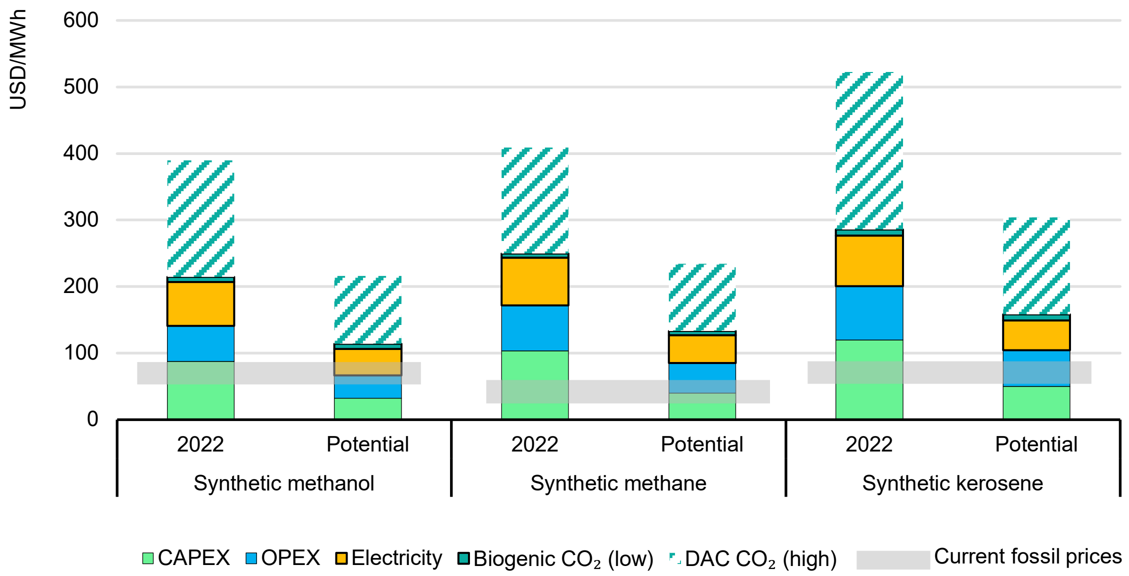
## $CO_2$-based fuel production

$CO_2$ utilisation can represent a revenue stream for capture facilities. New conversion routes use $CO_2$ as a feedstock for industrial processes producing various commodities such as synthetic fuels, chemicals, and building materials. The economic viability of these conversion pathways depends on a number of factors, including availability and performance of best available technologies, energy prices, market demand and supporting policies.

The current demand for synthetic fuels represents only a small fraction of the demand for fuels, but could increase over time in response to policies incentivising their use, such as low-emissions fuel mandates (e.g. for aviation in the European Union) or standards (e.g. the Low Carbon Fuel Standard in California). Robust, transparent and mutually agreed emissions accounting methods need to be in place to quantify emissions reduction and avoid double counting. This is particularly relevant for internationally traded synthetic fuels.

$CO_2$-based synthetic fuels require large amounts of energy to convert $CO_2$ – a very stable molecule – into something else. For their production to be low-emissions, the energy required for the process and to produce hydrogen also needs to be low-emissions, which can greatly influence costs. Another important cost factor is that $CO_2$ will need to increasingly be sourced from biogenic sources or from the air to achieve emissions reduction in a decarbonised energy system. In the short to medium term, $CO_2$ can be captured from existing bioenergy facilities at a cost ranging from USD 30/t $CO_2$ (biofuels) to USD 100/t $CO_2$ (biomass power plant). As these applications can be limited in scale by the availability of sustainable bioenergy supply, $CO_2$ feedstock can also be obtained from direct air capture (DAC) as the market scales up. While DAC does not face the same constraints, this can however result in a much higher $CO_2$ feedstock cost. In order to be competitive with their fossil counterparts, $CO_2$-based synthetic fuels would require very low-cost electricity or high prices on fossil emissions, or targeted incentives/mandates for low-emissions synthetic fuels.

**Levelised cost of $CO_2$-based fuel production, 2022**






Notes: CAPEX = capital expenditure; OPEX= operational expenditure. $CO_2$ feedstock cost 2022: lower bound: USD 30/t $CO_2$ (assumed cost of capture for a biofuel plant); upper bound: USD 720/t $CO_2$ (cost of capture for a DAC plant). $CO_2$ feedstock cost potential: lower bound: USD 30/t $CO_2$ (assumed cost of capture on a biofuel plant); upper bound: USD 430/t $CO_2$ (assumed cost of capture for a DAC plant in 2030).
Sources: Based on data from McKinsey & Company and The Hydrogen Council; NETL (2022); IEAGHG (2017).

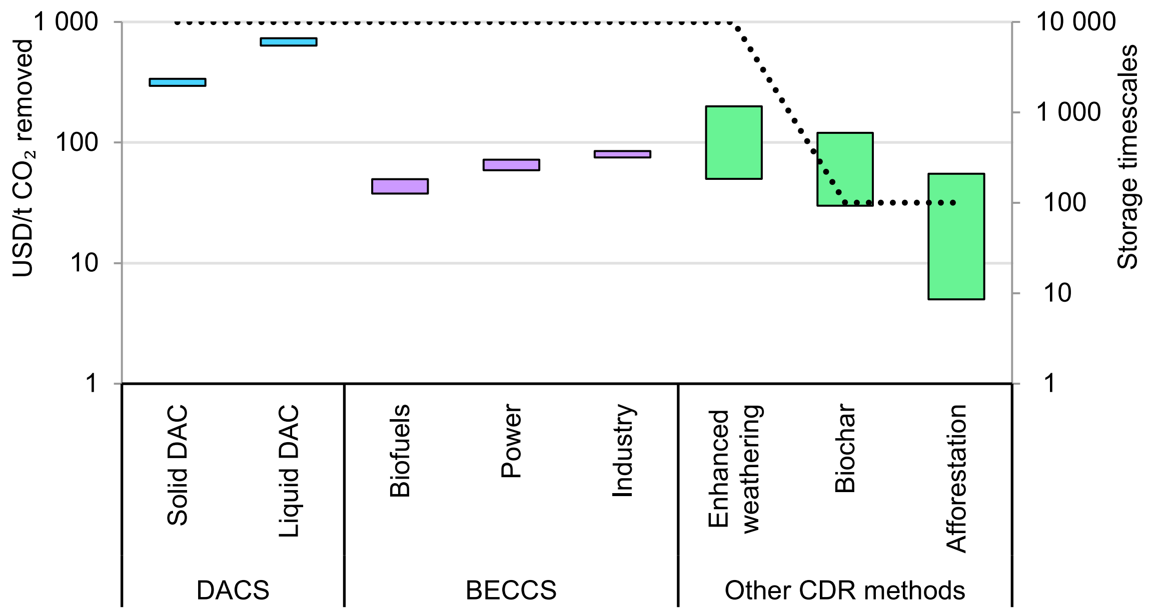
# $CO_2$ removal

The carbon dioxide removal (CDR) portfolio includes various approaches to capture $CO_2$ from the air and permanently store it so that it is effectively removed. CDR approaches include nature-based solutions (such as afforestation and reforestation), technology-based solutions such as direct air capture and storage (DACS) and bioenergy with carbon capture and storage (BECCS), as well as enhanced natural processes (such as enhanced weathering). BECCS indirectly removes $CO_2$ from the atmosphere through capturing the emissions generated during biomass refining or combustion, while DACS captures it directly from the atmosphere through liquid solvents or solid sorbents.

The cost of removal through DACS is typically higher than for point-source capture methods such as BECCS, due to both higher capital cost (DAC is a relatively new technology – with the first pilot plant commissioned in 2010 and the first kilotonne-scale plant commissioned in 2021) and higher energy requirements (due to the much lower $CO_2$ concentration in the air compared to its concentration in a stream from bioenergy refining or combustion). The cost of removal (see definition in Annex C) using DACS technologies depends on technology archetype and energy source, and can range between USD 300-730/t $CO_2$. That of BECCS depends on the application and overall life-cycle emissions from the BECCS value chain, with levelised cost of removal ranging between USD 40-50/t $CO_2$ for concentrated streams such as bioethanol and biodiesel, and between USD 60-85/t $CO_2$ for biomass-fired boilers (employed in both power and industrial production processes). The use of one technology or the other will depend on regional factors including availability of low-emissions electricity and waste heat, and of sustainable biomass supply.

While technology-based removal methods are generally more costly per tonne of $CO_2$ removed than nature-based CDR and enhanced natural processes, they are also characterised by higher storage timescales, with a high probability that most of the $CO_2$ will remain trapped for at least 1 000 to 10 000 years, while storage timescales for nature-based CDR are typically decades to centuries.

**Cost of removal and storage permanence for different removal methods**






Notes: DACS = direct air capture and storage; BECCS = bioenergy with carbon capture and storage; CDR = carbon dioxide removal. Biofuels include bioethanol and biodiesel. DACS cost of removal includes the cost of capturing and storing $CO_2$, including for indirect $CO_2$ emissions associated with DAC energy use. BECCS costs only include costs of capturing, compressing, transporting and storing $CO_2$ (and exclude costs associated with bioenergy production), and accounts for biomass life cycle emissions. $CO_2$ transport and storage: USD 30/t $CO_2$.

Sources: Alcalde (2018), IPCC (2021), EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Beerling (2020).

# Long lead times

## CCUS project structure and timelines

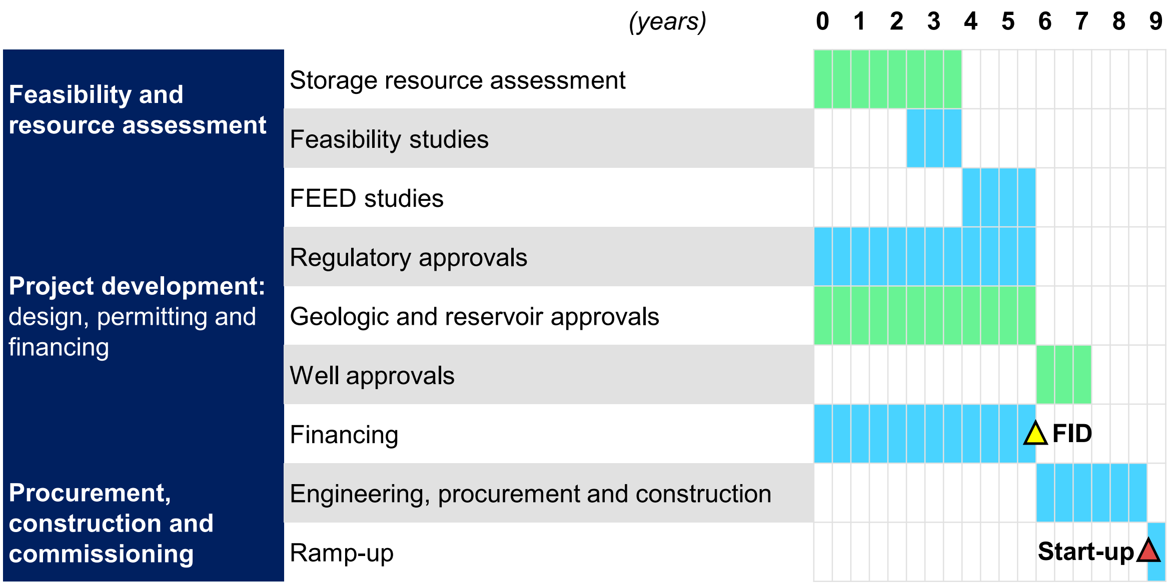
Developing a CCUS project from announcement to commissioning goes through different stages, including feasibility studies, design and development, and construction.

The objective of the **feasibility stage** is to assess the practicality and viability of the proposed project. For the capture and transport part of the chain, this stage aims to deliver the preliminary technical, economic, regulatory and environmental assessments of the facilities to determine whether the project can proceed; this stage can typically be completed within 1-2 years. For projects including geological storage, this step is particularly critical since it includes the **assessment of $CO_2$ storage resources**, which determine where, in what quantity, at what rate, and for how long $CO_2$ can be safely injected and stored. This requires numerous and extensive studies, modelling of the subsurface, drilling of test wells and seismic assessment, among other assessments. As a result, timelines for storage assessment can be years longer than for capture and transport feasibility, and therefore this step should commence well in advance.

The **development stage** aims to translate the outputs of the feasibility studies into detailed project specifications and planning, and to secure permits ahead of the final investment decision (FID). For capture and transport, this stage includes Front-end Engineering and Design (FEED) studies for capture and transport facilities, which can take around 2 years. Securing regulatory approvals, such as environmental, exploration and injection approvals, can be the most time-consuming step, and can take years, depending on jurisdictions, assuming that legal and regulatory frameworks are already in place.

The final investment decision (FID) on the project takes place sometime between design, and development and construction. At any point before the FID a project can be cancelled following an unfavourable assessment. Once a final positive investment decision is made, projects can proceed to detailed engineering, procurement, construction (EPC) and commissioning. This step can be more time-consuming for capture and transport facilities, which require procurement of a wide range of processing equipment and the construction of facilities, than for storage, for which less infrastructure is required. Overall this phase can take 2-4 years.

**High-level planning and indicative timelines of a CCUS project**



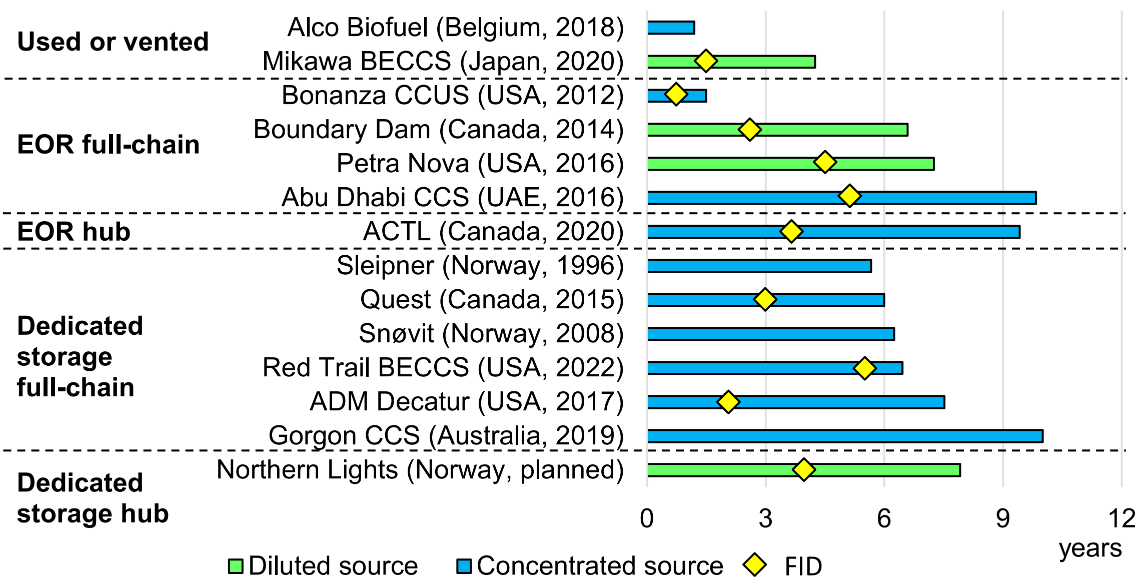



Note: FEED = Front-end Engineering and Design; FID = Final investment decision. Storage resource assessment may include site appraisal, subsurface modelling, seismic assessment, Monitoring, measurement and verification definition and planning.
Sources: IEA analysis adapted from Alberta Department of Energy, (2017), Alberta Carbon Trunk Line, (2020).

## How long have past projects taken?

CCUS projects already in operation have taken from less than 2 years to over 10 years from announcement to commissioning, with a median around 6 years. This wide range can be explained by the diversity of projects, in terms of application for $CO_2$ capture, fate of the $CO_2$ (dedicated storage or utilisation), and infrastructure requirements. In addition, most operating projects are first- or second-of-a-kind demonstration projects, often reliant on public funding, and subject to unique circumstances related to the lack of operational experience for certain CCUS technologies or applications.

**Lead times of selected operating and planned CCUS projects**






Notes: BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CCUS = carbon capture, utilisation and storage; EOR = enhanced oil recovery; FID = Final Investment Decision, UAE = United Arab Emirates; US = United States. Lead time is defined as time between first project announcement and commissioning. Mikawa BECCS projects ultimately aims to store the $CO_2$ but $CO_2$ is currently used or vented.
Source: IEA analysis based on IEA (2023), CCUS Projects Database.

The **fate of the $CO_2$**, and whether $CO_2$ storage resources need to be assessed, or $CO_2$ transport infrastructure constructed, is the first factor affecting project lead times. Projects which involve utilisation tend to have shorter lead times than projects involving dedicated storage. Developing a new $CO_2$ storage site can take 3-10 years: most of this is driven by the time it takes to develop resources. As an example, it took almost 4 years to complete subsurface modelling for the Quest project in Canada. EOR projects can typically be developed faster than dedicated $CO_2$ storage sites, given that the subsurface is already known and characterised thanks to ongoing oil and gas operations. This is also true for storage in depleted oil and gas fields, whose geology is already known. These projects still require extensive injection tests and risk assessments to ensure the permanence and safety of $CO_2$ storage.

The **source of the $CO_2$** can also have an important impact on lead times. Projects which involve $CO_2$ capture on concentrated $CO_2$ streams, such as in natural gas processing and bioethanol production, only require $CO_2$ drying and compression, whereas diluted streams, for example in electricity generation and industrial production, require the installation of a capture unit. It took less than 2 years to design and deploy $CO_2$ separation at the Bonanza bioethanol plant in the United States, while it took more than 6 years to design and deploy capture at the Boundary Dam coal-fired power plant.

**Securing regulatory approvals** can be a time-consuming step for all projects, but storage development requires specific exploration and injection drilling permits that can take years to obtain. This is likely to vary significantly across jurisdictions as permitting procedures are established and improved.

The **structure and complexity of the CCUS project**, whether it is a full-chain project connecting one capture source with one dedicated storage site, or part-chain project connected as part of a CCUS hub, and resulting infrastructure requirement, are other potential drivers of lead times. The Alberta Carbon Trunkline commissioned in Canada in 2020 is the first infrastructure project connecting two capture units to one injection site (for EOR). While development of the capture units took less than 6 years, the overall project took close to 10 years to reach commissioning, delayed by the difficulty of synchronising the various elements of the value chains.

**Securing financing** can also represent a source of delay. For operating projects, reaching the FID has taken on average the same amount of time as project construction. Most large-scale CCUS projects cannot operate without investment support and operational subsidies. This is particularly burdensome for those projects which cannot benefit from revenue streams related to $CO_2$ utilisation. Moreover, first- or second-of-a-kind projects suffer from high uncertainty in cost estimates, which tend to be revised upward between feasibility, FEED and EPC, with a risk of running over the allocated budget.

## Perspectives for future lead times

Accelerating project lead times is vital to bring the global deployment pathway into line with the requirements of the NZE Scenario. There is potential for lead time reductions. The next generation of projects can benefit from learnings from past projects, both in terms of technical specifications and streamlining regulatory approvals. For example, the Red Trail BECCS Energy project, the second-of-a-kind bioethanol capture project injecting $CO_2$ for dedicated storage, took 1 year less to complete than the Decatur ADM project. Governments are also implementing measures to reduce permitting and licensing lead times, such as in the United States and European Union (see Chapter 5).

Modularisation can also help reduce project lead times. While retrofitting capture units from feasibility to commissioning took around 6 years at the Quest plant, some companies are offering modular end-of-pipe capture units which could be deployed over a period ranging from 24 to 30 months.

Projects that connect to existing $CO_2$ management infrastructure could also benefit from reduced lead times, with the potential to be completed in 4 years or less. However, as projects move towards a hub structure, with complex networks connecting multiple facilities and $CO_2$ storage sites, there is also a risk that the first hubs take longer to develop than full-chain projects. Construction is underway for the Northern Lights project in Norway, which could be the first operating transport and storage hub in Europe, with a targeted commissioning date in 2024. If the project is completed on time, the project would have taken around 8 years to reach commissioning. Brevik Norcem, the first large-scale CCUS unit applied to a cement plant, which would connect to the Northern Lights storage hub, would also have a lead time of just over 8 years, if completed on time. Government co-ordination between $CO_2$ storage developers and emitters, and a phased approach to hub capacity, can help reduce these lead times.

Large networks spanning over extended areas also present the risk of facing more social opposition, causing further delays. This is, for example, the case for plans by company Navigator to develop a pipeline network spanning five states, which were just cancelled amidst permitting hurdles. Another 3 000 km pipeline planned to connect more than thirty bioethanol facilities in the United States across a five-state region is currently facing opposition from local land-owners that has caused delays in securing permitting. Engaging with local stakeholders early in the process and emphasising the social benefits of planned projects is important to reduce potential delays (see Box on “Enabling social acceptance of CCUS by showing community benefits” in Chapter 5).

# Project complexity

The shift toward the CCUS hub model provides many benefits (see Chapter 3), but also means that project structure is increasingly complex, with implications for risk, timing, co-ordination and social acceptance.

## Project risks

CCUS projects present a range of risks which need to be carefully managed. These include technical, market, cross-chain, social, regulatory, environmental and legal risks.

### Overview of potential risks for CCUS projects

| Types of risks | Description |
|---|---|
| Technical | Relates to technical failure of all or part of the CCUS value chain, which could impact the overall network. |
| Cross-chain risks | The risk that failure or unavailability of part of the chain impacts other actors in the chain. |
| Market & financial | Fluctuations in carbon prices, energy prices and other market factors can impact the viability of a CCUS project. |

| Types of risks | Description |
|---|---|
| Legal | Determining liability in case of leaks, accidents or negative environmental impacts can be complex and could result in legal disputes between parties involved in CCUS projects. Attributing long-term liabilities associated with $CO_2$ storage can be particularly challenging. |
| Regulatory | As regulatory frameworks for CCUS are being implemented or updated around the world, changes in regulation and policies could impact the feasibility or economics of CCUS projects. |
| Climate | Failure to contain $CO_2$ in storage sites could result in $CO_2$ re-release and therefore the reversal of CCUS mitigation effects. |
| Health, safety, and environment | **Capture**: Solvent degradation in air, if unmanaged, could present toxic risks to the exposed population.<br><br>**Transport**: $CO_2$ leaks in a high-pressure transport system could pose health and safety risks for operators and local populations.<br><br>**Storage**: Injected fluids can activate either known or unknown faults and cause seismic events, or interact with other subsurface resources. |
| Social acceptability | Communities near storage sites or along transportation routes might oppose CCUS projects due to fears of leaks, accidents, or other negative impacts on their surroundings. The wider population could also oppose funding for CCUS projects owing to lack of trust in the technology. |

Moving from full-chain projects to complex CCUS hubs can impact the project risks, particularly with regards to the following aspects:

**Counter-party risks**: greater co-ordination is required between stakeholders within a CCUS hub to ensure syncing of emissions sources and sinks on the value chain. A diverse group of emitters and sinks can make the network more resilient, but the design of CCUS networks must take into account when different sources and sinks become available and at which capacity.

**Legal**: allocating liabilities across stakeholders can be more complex. However, in a CCUS hub, risk provision can be shared among a greater number of actors.

**Market and financial**: Large CCUS hubs enable cost-sharing among emitters but require greater up-front investment than full-chain projects.

**Social acceptability**: CCUS hubs require infrastructure which may span large areas, increasing the potential for social opposition.

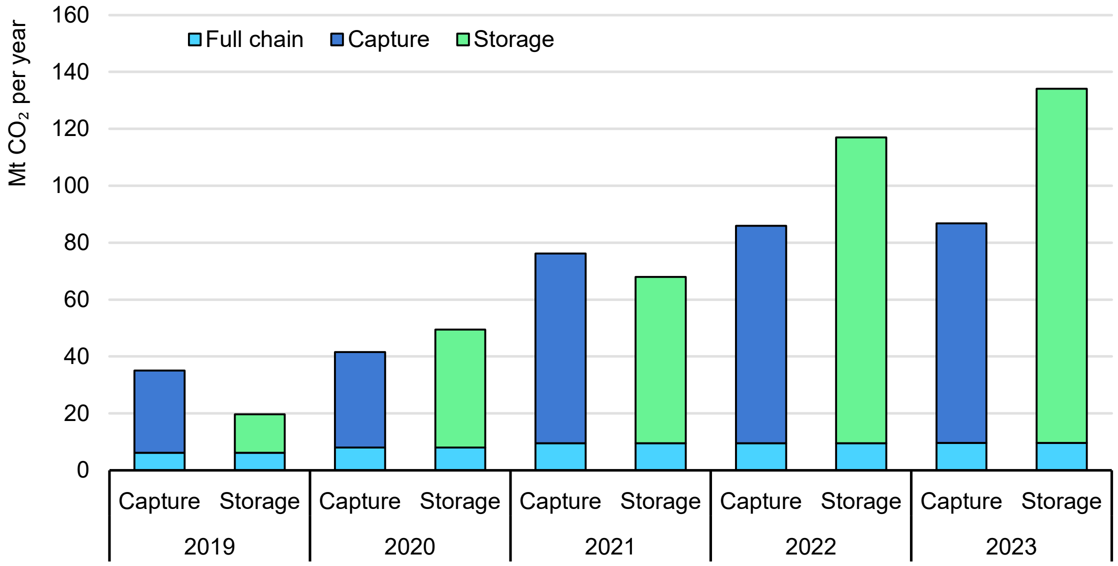
These risks need to be addressed through proper project planning, thorough risk assessments, transparent communication with stakeholders, adherence to regulatory guidelines, and ongoing monitoring and maintenance.

## Cross-chain co-ordination

As the CCUS value chain is broken into smaller projects, it is essential that capture and storage developments track each other. $CO_2$ emitters require $CO_2$ transport and storage infrastructure to be available to start planning their project, while developers of $CO_2$ management services need to secure demand through offtake agreements with $CO_2$ emitters if they are to invest in costly $CO_2$ infrastructure. Matching emissions sources to potential sinks can be used to design optimal $CO_2$ networks at the regional level. Governments have a key role to play in planning the development of CCUS hubs, for example through funding these source-sink matching studies.

Until 2021, global $CO_2$ storage plans were lagging behind capture plans, but increased focus on developing storage resources has helped to boost the development of the entire sector. For example around the North Sea, initiatives from Denmark, Norway, the Netherlands and the United Kingdom to accelerate $CO_2$ storage explorations in the area led to a rapid increase in both capture and storage plans.

**Capture and storage capacity in planning around the North Sea, 2019-2023**






Notes: Assessment includes the following countries: Denmark, Iceland, Norway, Sweden, the Netherlands, and the United Kingdom. 2023 data refer to estimated data as of June 2023.
Sources: IEA (2023), CCUS Projects Database.

Co-ordination becomes particularly critical in a hub model, as hubs typically involve oversized infrastructure with higher $CO_2$ management capacity in order to cater for future demand. The average size of $CO_2$ storage hubs in planning across the world is over 5 Mt $CO_2$ per year, around four times greater than the average size of capture projects.

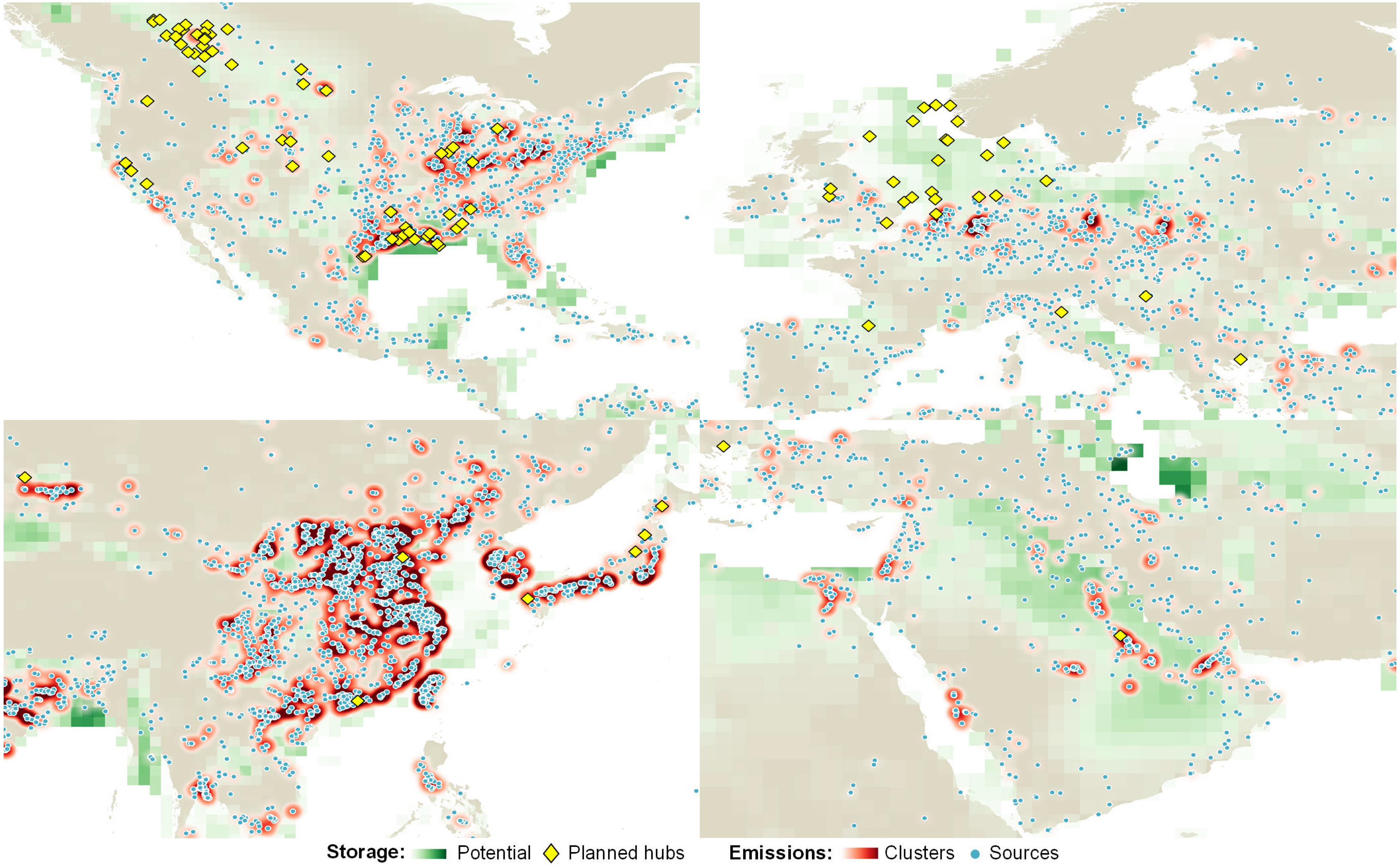
A phased approach to developing transport and $CO_2$ storage projects is required to minimise the risks of over- or under-sizing the system. For example, the Northern Lights transport and storage project in Norway is considering a third expansion phase to meet demand from emitters who have expressed interest in connecting. This third expansion would be more than six times greater than the planned capacity of the first two phases combined. A phased approach can also allow for changes in financial support, with the first phase of Northern Lights being supported by government, and the second and third aiming to be commercial.

## Access to $CO_2$ management infrastructure: sectoral and regional considerations

Some emission-intensive applications are more suited to being part of an industrial cluster and therefore being an ideal target for a CCUS hub than others. For example, oil and gas, chemical and petrochemical production plants are frequently located in close proximity to each other due to their feedstock interdependency, and while power plants are fairly evenly distributed, they are usually large-scale and therefore emission-intensive. In contrast, cement production plants tend to be smaller and more dispersed. BECCS facilities, including biofuel, power, waste-to-energy, and pulp and paper plants, also tend to be smaller scale and more dispersed, often close to sustainable bioenergy feedstock, the production of which is widely spread, or close to urban centres if relying on municipal solid wastes.

Moreover, $CO_2$ management infrastructure needs will not be the same across each region, depending on numerous factors including geography, storage potential (whether onshore or offshore), industrial economy and population density. The structure of CCUS hubs and infrastructure networks – either through a linear trunkline spanning a large area, or local collecting pipelines connected to terminals for $CO_2$ shipping over longer distances – needs to be adapted to different regional contexts.

**$CO_2$ emissions clusters and storage hubs in planning in selected regions, 2023**






Notes: Point sources and $CO_2$ emissions clusters include steel, cement, chemical, power generation and refining in facilities with total emissions larger than 0.1 Mt $CO_2$ per year. Sedimentary thickness (km) is used to indicate theoretical potential of $CO_2$ storage sites. Sources: Analysis based on US EPA Office of Atmospheric Protection (2021); European Commission (2021); Kearns et al., (2017); S&P Global (2022); Global Energy Monitor, (2022); Global Cement, (2022).

Globally, our analysis shows that around 60% of global cement plant emissions are within 30 km of industrial clusters,[18] compared with 80-90% for steel, power, and chemicals emissions.

In North America, around 70% of emissions from steel, chemicals, cement, power, and refining plants are within 30 km of emissions clusters, many of which are in the close vicinity of the many onshore $CO_2$ storage hubs currently under development. The picture is different in Europe, where most $CO_2$ storage hubs are being developed in the North Sea, even though only around 15% of emissions are within 100 km of ports on the North Sea coast. Cement plants are particularly dispersed, with only 25% of the sector's emissions close to industrial clusters. Developing infrastructure to reach dispersed and smaller emitters, particularly in landlocked countries, will be crucial.

In China, around 90% of emissions could be within industrial clusters but only a few storage hubs are currently under planning. In the Middle East, this share goes down to around 70%, and only one storage hub is currently in planning.

## Multimodal and cross-border $CO_2$ management infrastructure

Depending on geography and on the location of emitters and geological resources, large CCUS hubs may require more complex multi-modal transport systems. These can involve ships, pipelines and trains, but also $CO_2$ terminals, liquefaction facilities and storage tanks. This more complex, potentially cross-border infrastructure can pose several challenges.

**Legal and regulatory**: Transporting $CO_2$ across borders involves navigating international regulations and agreements related to environmental protection, transportation and trade. Different countries might have varying rules and standards for transporting hazardous materials. The London Protocol allows for storage of imported $CO_2$, as long as bilateral agreements have been signed between the two countries. Determining liability and jurisdiction in the case of accidents, leaks or other incidents during transport can be complicated when crossing international boundaries.

**Permitting**: Obtaining the necessary permits and approvals from multiple jurisdictions can be time-consuming and may require compliance with a variety of regulatory frameworks. Delays in permitting can impact project timelines and costs.

[18] Here defined as clusters of emissions greater than 5 Mt $CO_2$ per year.

**Technical compatibility and $CO_2$ properties**: $CO_2$ can be transported in different phases (e.g. gaseous, liquid, dense) under different pressures and temperatures. Maintaining the appropriate phase during transport is essential for safety and efficiency, particularly when switching from one mode to another (e.g. from pipeline to ship). Ensuring compatibility across various systems in terms of $CO_2$ properties and impurities is also required.

**Carbon accounting**: The potential for varying standards and requirements between nations can complicate the certification process, leading to ambiguities in the validation of carbon credits.

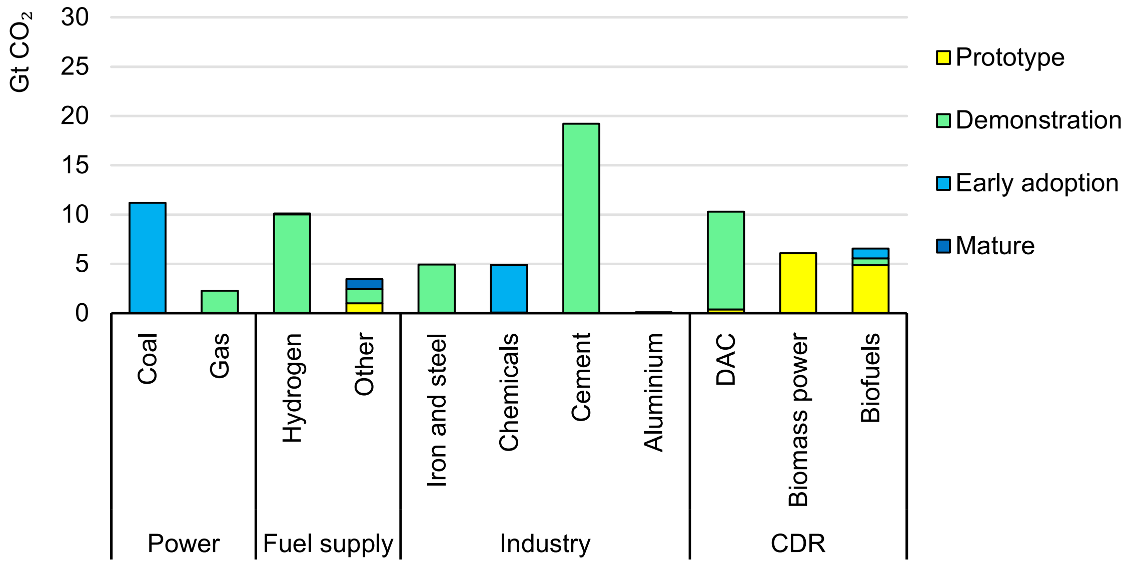
Addressing these issues requires effective international collaboration, harmonisation of regulations, transparency, robust risk assessment and management, investment in infrastructure, and ongoing communication with stakeholders. As the development of cross-border and multi-modal $CO_2$ transport projects increases, it is important to consider and manage these challenges to ensure safe and efficient transportation of $CO_2$.

# The innovation gap

The successful scale-up of CCUS depends on the timely development of a range of capture, transport, storage and utilisation technologies. The CCUS applications that are mature today are not necessarily the ones consistent with the NZE Scenario. For instance, capture on natural gas processing plants (one of the few mature CCUS technologies to date) makes up just around 1% of cumulative capture needs by 2050 in the NZE Scenario, owing to a phase-down in oil and gas demand. Around three-quarters of planned capture capacity by 2050 in the NZE Scenario relies on technologies that are still at demonstration or prototype scale. While this is significant, this gap in technology maturity can be quickly reduced with a handful of technologies being demonstrated (e.g. capture in a large-scale cement plant). Around 40% of planned capacity which relies on technology at demonstration stage or below is in industrial applications, which makes up a third of cumulative captured $CO_2$ to 2050.

$CO_2$ removal is another area with a strong need for demonstration. DAC has made progress in the past two years, moving to the demonstration stage with the first kilotonne scale plant entering operation in 2021. Capture on utility-scale biomass gasification plants and advanced biofuels facilities, however, is still at the prototype scale.

**Cumulative $CO_2$ captured by Technology Readiness Level (2022-2050) in the Net Zero by 2050 Scenario, by sector**






Note: CDR = Carbon dioxide removal. Technology Readiness Level (TRL) between 4 (early prototype) and 6 (full prototype at scale); demonstration: TRL between 7 (pre-commercial demonstration) and 8 (first-of-a-kind commercial); early adoption: TRL between 9 (commercial operation in relevant environment) and 10 (integration needed at scale); mature: TRL 11 (proof of stability reached).

Source: IEA (2023), Clean Energy Technology Guide.

With regards to the regional distribution of innovation needs in the NZE Scenario, emerging economies have a lower share of planned capacity relying on technologies at a lower TRL than advanced economies. This is mostly driven by a relatively larger demand for capture retrofits on existing power facilities, which rely on state-of-the-art post-combustion chemical absorption, while more CDR is deployed in advanced economies. However emerging economies account for a large part of cumulative $CO_2$ capture by 2050 in the NZE Scenario, which means the innovation gap is greater in absolute terms. Additionally, some technologies that have been demonstrated in advanced economies have not yet been demonstrated in emerging markets, where only around 30% of operating capacity is concentrated today. International technology and knowledge transfer will be required to bridge the innovation gap in emerging markets.

# Chapter 5: A policy toolkit to accelerate deployment and build a commercial market for CCUS

As Chapter 2 outlines, policy makers have at their disposal a suite of instruments, or tools, to facilitate and promote the deployment of carbon capture, utilisation and storage (CCUS) projects. Experience has shown that layering or stacking various policies across different categories can help address different risks that a CCUS project may face.

Yet, the current policy landscape for CCUS – while promising – is insufficient to build a viable and sustainable business case in many regions around the world. Enabling legislation and rules and cost reduction measures, primarily, have contributed to the successful deployment of projects today. But beyond these "low-hanging fruit" approaches, other categories of policies that regulate industrial activities, send strategic signals and allow for the creation of revenue streams are needed to scale up CCUS.

Governments do not need to reinvent the wheel: policy makers can look to other sectors or policies for clean energy technologies to address these gaps and challenges. In fact, many governments are already using the regulatory learnings from other parts of the energy sector and applying aspects of successful policies in the context of CCUS.

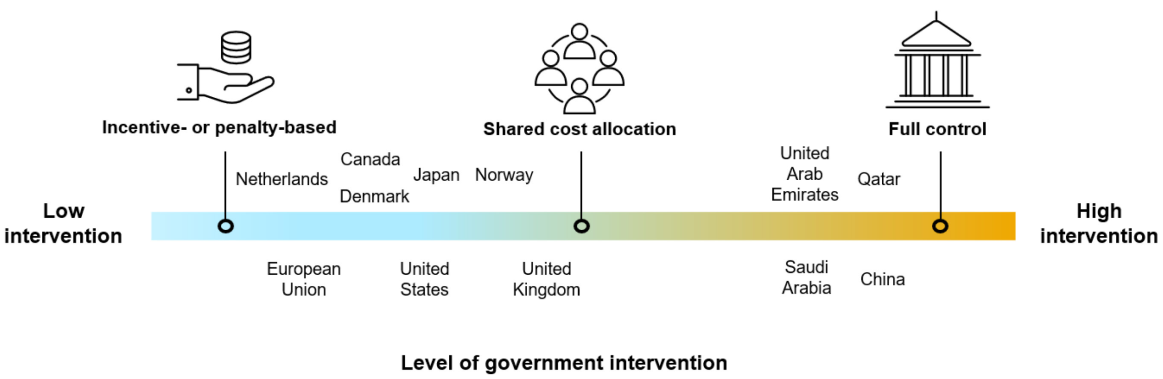
## Overview on types of approaches to build a commercial market

Each government may take a slightly different approach to establish a viable and sustainable market for CCUS. One point is clear: there is no one-size-fits-all way to approach building a commercial market. Instead, various approaches should be thought of as existing on a **spectrum** – on the one end, governments can use incentive- or penalty-based policies (a "carrot-and-stick" approach) to drive private sector decision-making; on the other end, governments fully control what the market will look like and its design; and in the middle, governments are more involved in some aspects of market design, but not all. This is not unlike the spectrum of economic regulation, with laissez-faire capitalism at one end and centralised economic planning at the other.

A number of institutional, economic and political factors will influence what part of the CCUS policy spectrum a country may end up on. And it is important to note that countries may move along the spectrum as these factors change and as the domestic market for CCUS evolves. For example, Norway and the United Kingdom are taking very active roles in establishing a market for CCUS, both focusing on providing large amounts of support for first-of-a-kind projects (with Norway covering around two-thirds of the costs of the Longship project, and the United Kingdom taking on $CO_2$ leakage risks in the absence of commercial insurance solutions). Later, these countries plan to transition to a lower-intervention phase as the commercial market develops. Likewise, countries can exist across parts of the spectrum as policies also change, and where a country sits on the spectrum may dictate the types of policy tools used to promote CCUS deployment.

Of course, there are trade-offs between different approaches: a low intervention approach may result in faster outcomes, but those outcomes may not necessarily be aligned with government goals, whereas as a high intervention approach may prioritise policy goals over speed.

**Spectrum of existing approaches to building a commercial market for CCUS**






# Incentives- or penalty-based systems

In an incentives- or penalty-based system, often referred to as a “carrot-and-stick” approach, countries use policies to influence how a private company will make its investment decisions. This is either done with **incentives**, whereby the government offers subsidies such as grants, loans or tax credits to private companies to deploy a certain technology or adopt a certain practice, or with **penalties**, whereby private companies are penalised via taxes or fees for not complying with regulations, or are bound to deployment or product mandates. The incentive-based system has the advantage of providing the private sector with substantial funding, however, there is no guarantee these incentives will be picked up, if poorly designed. That is often the case for incentives that focus on capital expenses but leave out operational costs, or for funding that is too prescriptive in terms of supported applications/technologies, or too strict on the timelines of the major project milestones (Front-End Engineering and Design [FEED], commissioning, etc.). While this approach may involve a lower level of government intervention, it may still benefit from some level of government co-ordination of activities.

The **United States** and **European Union** tend to follow this approach for deploying CCUS projects, relying on incentives (i.e. tax credits and grants) and penalties (i.e. carbon pricing) to drive investment in CCUS.

## Shared cost allocation approach

In a shared cost allocation approach, governments do not solely rely on the market to incentivise private sector decision-making. For some capital-intensive activities with unclear revenue streams (such as the development of electric grid infrastructure), governments have stepped in to ensure a viable business case for these markets, offering to share the allocation of costs between the public and private sector. Under this approach, if the activity is provided by a private company, economic parameters govern the revenue and profit structures of the project, such as under a **regulated asset base** model. The shared cost allocation approach may be a good fit for large infrastructure endeavours, such as the development of a $CO_2$ transportation and storage network, but it also requires more continued government support over a longer timeframe than grants or tax credits, for instance. This is why it is crucial to design it as part of a long-term decarbonisation strategy, going beyond the single election cycle and annual government budget.

The **United Kingdom** is one example of this with its Transport and Storage Regulatory Investment (TRI) model to build out $CO_2$ transport and storage infrastructure. The United Kingdom is also an example of a country that has moved along the spectrum for CCUS policy approaches: before the TRI proposal, the United Kingdom relied more on the incentive- or penalty-based approach, and now it is also employing a shared cost allocation approach. The **United States** is also starting to use this approach, though to a much lesser extent, under its shared access requirements in the USD 2.1 billion CIFIA loan programme for $CO_2$ transport projects.

## Full control approach

Instead of relying on the private sector to develop a market, the full control approach leans on a country's **state-owned enterprise (SOE) system**. In the case of CCUS, this means that SOEs are not only investing in CCUS projects, but could also develop and operate them. The advantages of this approach are that the government is better able to control the number of CCUS projects that are deployed and to overcome potential investment and financing challenges that private firms may face. However, this approach relies heavily on internal expertise at state-owned companies, which may act as a barrier to initial deployment. This approach still relies on some level of private sector involvement, whether through jointly developing projects, or as a customer or investor.

**China, Saudi Arabia, Qatar** and the **United Arab Emirates** are examples of this approach, where the vast majority of CCUS projects in operation and under development are through an SOE. Despite this, there is still some level of involvement from private companies, depending on the country.

## How can policy effectively and efficiently tackle existing gaps and challenges?

Governments have several policy tools at their disposal and can take a number of approaches with varying levels of government intervention to address challenges to CCUS deployment.

Chapter 2 shows that existing policies also leave gaps that fail to address key challenges for CCUS, such as a lack of diverse revenue streams, low demand for low-emissions products, and a lack of standards and certifications for carbon dioxide removal (CDR) solutions. Chapter 4 further expands on the gaps where policy is lacking and outlines four main challenges for future CCUS deployment: economic viability, lead times, innovation and project complexity.

Governments are also testing new policy tools to address these gaps and challenges, and in some cases are drawing on lessons learned from other parts of the energy sector. Policy makers do not need to use every tool, and in fact some tools on their own will not be enough, but should instead evaluate which tool (or more likely, which combination of tools) will work best in their jurisdictions.

It is important that any tool or approach is both *effective* and *efficient*, setting up a viable and sustainable commercial market for CCUS that attracts investment and retains it over the long term.

Effective policies for CCUS work to address the variety of challenges facing projects. They allow private sector investment to flow into projects without creating a restrictive regulatory environment or allowing for excessive private profits from taxpayer-funded programmes. A balance must be struck between stimulating investment and achieving policy goals, while being mindful of not over-regulating a new commercial market. Ultimately, governments need to assess the level of risk they are willing to take on. This applies both in the sense of traditional project and financing risks, but also the risks associated with ineffective policies. A balance needs to be struck to ensure publicly funded efforts deliver value for taxpayers: too stringent and prescriptive a policy may result in lock-in of specific technologies or approaches; yet too unclear a policy may result in confusion and lack of adoption.

Efficient policies have a two-way flow of benefits that not only help CCUS, but also other clean energy technologies. For example, policies that target challenges to CCUS deployment – such as reforming permitting to reduce lead times or the co-ordination of hub infrastructure – can have knock-on benefits for other clean energy technologies. Likewise, policies that target other clean energy technologies – such as renewable energy deployment and transmission infrastructure build-out – can have knock-on benefits for CCUS, particularly for direct air capture (DAC) projects that may rely on low-emissions sources of electricity.

# Conclusions

Enabling legislation and rules (such as the establishment of legal and regulatory frameworks) and cost reduction measures (such as grants, tax credits, loan support and SOEs) have helped projects in operation today. This has had an impact on deployment, specifically in the types of applications. For example, low-cost applications such as natural gas processing currently make up the majority of CCUS deployment. But in order to decarbonise other sectors and scale up CCUS at the pace needed in the NZE Scenario, we need a portfolio of options to address the challenges we are seeing today.

Policy support is needed across all categories. Further support in enabling legislation and rules can help to address lead times and project complexity challenges. Expanded regulation of industrial activities and revenue support policies can address economic viability challenges. And international collaboration can cover cross-cutting issues that cannot be addressed by one single country.

As mentioned earlier, governments may shift their approach (incentive- or penalty-based, shared cost allocation, full control) as the CCUS market develops. This follows through for some of the tools that governments choose to use. For instance, policy tools for cost reduction measures (such as grants, tax credits and loans) may help bring down the cost of large-scale projects and help address some of the initial cost challenges to get projects off the ground. But these tools alone cannot create an economically sustainable commercial market for CCUS. Governments should turn to other policy tools to address all the challenges associated with CCUS deployment and ensure that investment continues to flow into CCUS projects, and these projects are completed on time.

While governments may choose to use certain policy tools at different stages of market maturity, the *simultaneous use of several tools* to address the array of challenges is the most effective way to drive investment. Governments should find a balance – this is the best way to ensure sustained investment and the timely roll-out of CCUS projects.

### Policy tools to address challenges to CCUS deployment

| Challenge | Policy categories to address challenge | Specific policy tools |
|---|---|---|
| **Economic viability** | Cost reduction measures<br><br>Regulation of industrial activities<br><br>Revenue support<br><br>International collaboration | Grants<br>Tax credits<br>Loan support<br>State-owned enterprises<br>Carbon pricing and leakage policy<br>Public procurement<br>Low-emissions mandates<br>(Carbon) contracts-for-difference<br>Regulated asset base<br>Emerging market and developing economy considerations: concessional finance, sustainable debt, and multilateral funding instruments |
| **Lead times** | Enabling legislation and rules | One-stop shop for permitting<br>Clear permit approval timelines<br>Internal regulatory capacity<br>Precompetitive resource assessments<br>Data sharing and transparency requirements<br>Community engagement requirements |
| **The innovation gap** | Cost reduction measures<br><br>International collaboration | RD&D<br>Platforms for international co-operation<br>Foreign direct investment for technology co-development |
| **Project complexity** | Enabling legislation and rules<br><br>Strategic signalling<br><br>International collaboration | Long-term storage liability<br>Competitive solicitations for CCUS hubs<br>One-off backstop agreements for first movers<br>London Protocol specifications<br>Definition of high-quality removals<br>Robust measurement, reporting and verification mechanisms |

## Enabling legislation is necessary to establish a legal foundation for CCUS…

As Chapter 2 outlines, enabling legislation and rules *facilitate* CCUS deployment, rather than promote. This often involves the establishment of legal and regulatory frameworks for CCUS, which set a legal basis for CCUS activities, such as allowing for the geological storage of $CO_2$ and putting in place measuring, monitoring and verifying requirements for the $CO_2$ once it is stored. Legal and regulatory frameworks exist in over 20 jurisdictions around the world and have helped contribute to a number of CCUS projects in operation today.

In the IEA CCUS Handbook on Legal and Regulatory Frameworks, we identify 25 priority legal and regulatory issues for CCUS deployment that are broadly grouped into eight categories (defining the regulatory scope, environmental reviews and permitting, enabling first-mover projects, ensuring safe and secure storage, addressing long-term storage liabilities, international and transboundary issues, facilitating CCUS hubs, and other emerging issues).

Establishing a legal foundation for CCUS activities can help set the stage for greater CCUS deployment and should therefore be considered as a priority for facilitating deployment.

## …yet more efforts on this front are needed to facilitate projects

While legal and regulatory frameworks provide an initial baseline level of support, more enabling legislation and rules are needed to facilitate CCUS projects. For example, clarifications on **long-term liability** within existing frameworks can provide more certainty to project developers, and **permitting support**, **data sharing** and **community engagement** can help ensure projects are completed on time and with the public's support. In addition, strategic signalling, such as through **competitive solicitations,** can increase co-ordination across industries.

These efforts do not necessarily require public subsidies, but rather changes in processes and increased co-ordination to address key challenges to CCUS deployment. When combined, these policies can work to reduce **long lead times** and **project complexity** challenges.

### Long-term liability of stored $CO_2$

To address project risks associated with the long-term storage of $CO_2$ and reduce project complexity challenges, it is important that governments have the processes and mechanisms in place to address **long-term liability**. Long-term liability of stored $CO_2$ can generally be addressed in one of three ways:

- A provision is made for the transfer of liability to the relevant authority. In this case, the operator is generally required to meet a number of stringent conditions to ensure that there are negligible risks of future leakage before transferring liability of the storage site to the relevant authority.
- Long-term liability explicitly rests with the operator. Monitoring and reporting requirements remain in order to ensure safe and secure storage, though the frequency of reporting requirements may vary.
- Long-term liability is not explicitly addressed, with the implication that the operator would retain responsibility for the storage site in perpetuity (in some cases, the operator may be state-owned; therefore, the issue of transferring liability may not arise).

## Permitting support

Complicated planning and permitting regimes may put upward pressure on lead times. CCUS projects can span multiple regulatory jurisdictions, requiring project developers to secure permits across different parts of national and sub-national governments. In addition, approval timelines may not always be clear.

To address planning permitting shortfalls, governments can establish a **one-stop shop**, whereby a single regulatory body or a cross-government co-ordinating group is responsible for co-ordinating the planning and permitting process when it involves different government agencies. This body could also offer guidance and support on how to navigate planning and permitting frameworks if a proposed project involves multiple jurisdictions. Governments can also establish **clear permit approval timelines, requirements and guidance**, with flexibility built into regulations to give projects the opportunity to apply for application extensions. This can enable developers to better plan project timelines and reduce regulatory bottlenecks, though governments must find a balance between cutting regulatory red tape while also maintaining proper environmental and societal considerations. It is important that governments build **regulatory capacity** and provide regulatory bodies with the necessary resources and capacity to oversee and undertake permit approvals. This includes ensuring adequate funding, technical expertise and staffing to review and process permit applications, as well as establishing channels of communication across government agencies to ensure smooth co-ordination.

Governments are already taking steps to reduce permitting and licensing lead times. In the United States, injection well approvals could be reduced to around 2 years, and in the United Kingdom $CO_2$ storage sites could be commissioned 4 to 6 years after the exploration license is awarded. In the European Union, reducing permitting lead time for decarbonisation projects, including $CO_2$ storage, is one of the objectives of the EU Net Zero Industry Act.

## Data sharing and transparency

Part of the challenge of developing CCUS projects is the lack of adequate data for $CO_2$ storage sites. Storage resources themselves can take between 2-6 years to develop due to the resource assessment process and related study requirements. As a result, resource assessment needs to begin well in advance of capture project development.

To address data shortfalls, governments can accelerate a region's level of storage readiness by conducting **precompetitive resource assessments**. As part of this, dedicated data acquisition programmes can include drilling, geochemical and hydrogeological studies, seismic campaigns and regional mapping. Country or regional assessments may successfully end with the development of a resource atlas, or a portfolio of resources earmarked for further assessment. Site-specific assessments can aim to develop one or more $CO_2$ storage sites. **Data sharing** and **transparency** efforts, such as working with the existing oil and gas industry, can help. Governments will need to work with industry on the type and amount of data that should be made available, as some information may be considered proprietary and confidential for competitiveness reasons.

**Data sharing and transparency efforts for $CO_2$ storage in the United Kingdom and European Union**

Data access and availability for $CO_2$ storage resources are an important component for companies seeking to develop storage sites, not to mention that increased data transparency can also help build public trust. The United Kingdom and European Union are both making efforts on this front.

In the **United Kingdom**, the North Sea Transition Authority (NSTA), the country's $CO_2$ storage regulator, requires storage license holders to retain and report information and samples gathered as part of activities associated with the geological storage of $CO_2$. As part of this effort, the NSTA is allowed to publicly disclose this information after a suitable confidentiality period. The goal of this public information campaign is to help maximise the United Kingdom's $CO_2$ storage potential by enhancing the collective knowledge of the CCUS industry, allowing for best practices to be shared in order to support the quick development of the industry as a whole.

In the **European Union**, the proposed Net Zero Industry Act puts dual pressure on member states and oil and gas companies to disclose data related to $CO_2$ storage. The Act would require member states to publish "areas where $CO_2$ storage sites can be permitted on their territory", an important step to creating a larger, regional $CO_2$ storage atlas. For oil and gas companies, the Act would require the licensees of oil and gas production sites in the European Union to "make publicly available all geological data relating to production sites that have been decommissioned or whose decommissioning has been notified to the competent authority."

## Community engagement

It is vital that CCUS projects not only provide benefits in terms of emissions reduction or removal, but also that they positively impact local communities. Public opposition to CCUS projects can cause unforeseen delays, increasing costs and even potentially resulting in the cancellation of a project.

To increase stakeholder engagement, governments can encourage companies to engage project stakeholders early on in the project planning process. Engagement should not only involve a public consultation process, but also show how the local project can benefit the community. Governments can do this through a **community engagement requirement** in the issuance of public funds for a project. It is vital to receive public buy-in for projects and show community benefits for CCUS projects.

**Enabling social acceptance of CCUS by showing community benefits**

CCUS projects are complex and often involve large infrastructure requirements, passing through several communities and affecting a variety of stakeholders. For onshore projects, this can include the installation of long-distance $CO_2$ pipelines or storage sites that cut across multiple residential, commercial and public landowners. Offshore projects tend to concern a smaller number of property owners, but $CO_2$ shipping lanes and offshore pipelines may have interactions with existing maritime industries and activities.

Securing public buy-in to CCUS projects is not only vital to successful long-term deployment, but it is also sensible business practice. Early engagement of the communities affected by a CCUS project can help mitigate potential opposition, which has been shown to lead to the cancellation of large projects in extreme cases.

For example, in the Netherlands, public opposition to Shell's proposed CCUS demonstration project in Barendrecht delayed the project's implementation and contributed to its eventual cancellation in 2010. Public opposition to the project grew over the course of several years, as unanswered initial concerns had a "snowball effect", leading to an eventual distrust of the project.

More recently, in October 2023 the Heartland Greenway $CO_2$ pipeline project in the United States was cancelled due to "unpredictable" regulatory proceedings in multiple states, fuelled in part by landowner opposition to the nearly 2 100 km pipeline. The project, which was designed to transport up to 15 Mt $CO_2$ per year from dozens of ethanol plants for eventual storage in Illinois, faced permit approval denials and delays in two states. In February 2023, the project restarted its permit process in Illinois after its first attempt failed due to a lack of agreement with landholders. In September, regulators in South Dakota denied the project's permit application, citing concerns about the pipeline's safety and the company's transparency, and a lack of support from landowners.

Involving project stakeholders early on in the development process is a critical component of building social acceptance. Lessons can be drawn from Shell's Quest CCS project in Canada, which created a Community Advisory Panel made up of local residents, members of the academic community and representatives from local government and regulatory authorities. The panel continues to provide a forum for stakeholders to provide input on the design and implementation of the project's measuring, monitoring and verification plan. Elsewhere, the Tomakomai demonstration project in Japan employed a sustained public engagement campaign which contributed to the project's success. The project developer, JCCS, designed and conducted public outreach with the objective of ensuring that local stakeholders in the city of Tomakomai (population 170 000) and surrounding areas understood the project, the safety and security of $CO_2$ storage, and the purpose of CCUS.

In the United States, the Department of Energy (DoE) is requiring all projects to submit Community Benefits Plans in their applications for public funding under the Infrastructure Investment and Jobs Act and the Inflation Reduction Act. The plans are based on four policy priorities: workforce investment; community and labour engagement; diversity, equity, inclusion and accessibility; and implementing a DoE initiative to drive investment to disadvantaged communities. In most cases, these plans are scored at 20% of the technical merit review of proposals for grants. When an applicant is selected, their Community Benefits Plan will be part of the contractual obligation of the funding recipient.

In the European Union, the CCUS Forum Working Group on public perception issued a paper in September 2023 that offers recommendations to the European Commission as it finalises its Industrial Carbon Management Strategy. A core pillar of the recommendations is the role that governments have in promoting and facilitating dialogue with the public on CCUS. This includes embracing a comprehensive approach to public engagement, integrating and involving stakeholders proactively and early on in the process.

## Competitive solicitations

CCUS projects are complex endeavours that need to be carefully managed and supported by an equally thoughtful policy environment that addresses multi-level, multi-sectoral challenges.

As outlined in Chapter 3, new business models for CCUS are introducing a part-chain model where separate entities deal with $CO_2$ capture and with $CO_2$ transport and storage, leading to a greater need for co-ordination among the various steps of the chain. The development of CCUS hubs across sectors also increases a project's complexity, impacting the risk structure of projects as it relates to cross-chain, legal, market and social acceptability risks.

Governments have a central role to play in the co-ordination and planning of hubs – this will be a key part of reducing a project's complexity. One way to co-ordinate hub development is through **competitive solicitations** that encourage collaboration across multiple sectors. These solicitations can be tied to public funding (as is the case in the United States and United Kingdom) or can be part of the government's leasing process for $CO_2$ storage resources (such as in the province of Alberta in Canada).

Governments can also reduce counterparty risks by providing assurances to projects either through **one-off backstop agreements** with specific projects or through **structural designs** within policies. For example, the Norwegian government has agreed to bear the risk in the Longship project in the event that part of the value chain does not perform its contractual obligations. However, this backstop is currently only intended for the Longship project. In contrast, the United Kingdom has designed its regulatory asset base model to ensure that the $CO_2$ transport and storage provider can still receive revenue in the event that a $CO_2$ capture project cannot perform. Likewise, the United Kingdom's dispatchable power agreement model proposes an availability payment to the power generator even if the transport and storage network is not available.

## Cost reduction measures can incentivise large-scale projects…

Existing policies and measures to reduce costs have contributed to operational CCUS projects to date. For example, **grants** have provided funding to cover some of the upfront costs associated with early CCUS projects, which tend to carry a higher risk than subsequent projects. The European Union's Innovation Fund and the United States' large-scale demonstration project funding under the Infrastructure Investment and Jobs Act are such examples. Grant support can be used to fund FEED studies, or even costs realised in the early years of the project (e.g. engineering, procurement and construction, commissioning, etc.). This binds the government for a shorter period of time and allows the private sector to develop more entrepreneurial opportunities.

In addition, governments have allowed CCUS projects access to certain **tax credits** and **loan support** to spur CCUS activity. Finally, depending on the country, governments have also leaned on their **state-owned enterprise** (SOE) system to shift some risk away from the private sector, indirectly reducing investment costs.

These cost reduction policies have, in part, proven effective at the start in funnelling investment to the early-mover, large-scale projects. In practice, however, the deployment of operational projects has trended toward the lowest-cost applications, such as natural gas processing. Experience has shown that these policies alone are insufficient to incentivise CCUS deployment in higher-cost applications, such as iron and steel, biofuels, synthetic hydrocarbon fuels, and aluminium.

# …but regulation of industrial activities and revenue support are needed for projects to scale up

In addition to cost reduction measures, governments can turn to other policy categories to build out support for CCUS. The regulation of industrial activities, through **carbon leakage policies**, **public procurement** and **mandates** for low-emissions products can drive demand and incentivise long-term investment. In addition, newer regulatory approaches to support revenue streams, such as **contracts-for-difference** (CfDs) and **regulated asset base** (RAB) models, can increase the business case for some projects.

Coupled together, these policies can work to address the economic viability challenges faced by CCUS projects and incentivise the diversification of CCUS deployment across applications at a pace and scale that is consistent with reaching net zero emissions by mid-century.

## Demand for low-emissions products

The market demand for low-emissions products (such as low-emissions steel, cement or fuels) and services is currently not strong enough to drive investment. Governments can step in and spark demand through **public procurement** policies and **low-emissions mandates**, which can increase the economic viability of low-emissions products.

We are already seeing some governments look at using public procurement policies to enable an initial uptick in demand for low-emissions products, including embodied carbon targets for new buildings in France, the Buy Clean Initiative in Canada, the Buy Clean Executive Order and Taskforce in the United States and accompanying procurement of low embodied carbon materials for construction, and Japan's GX League. In 2021 the Industrial Deep Decarbonisation Initiative launched the Green Public Procurement Pledge to encourage the public procurement of low-emissions steel and concrete. In addition to low-emissions products, the United States is also examining how to use public procurement to increase the CDR market. The US DoE announced USD 35 million in September 2023 to purchase offtake agreements for a portfolio of CDR pathways consistent with the objectives set out in its Carbon Negative Shot initiative.

**Low-emissions fuel standards** or **mandates** can achieve a similar effect. The Low Carbon Fuel Standard regulations introduced by California, Oregon and British Columbia (and under consideration in many other states and provinces) attracts a significant premium for fuels that meet lower carbon intensity standards. The same idea can be applied outside of low-emissions fuels and to low-emissions materials and products.

## Carbon pricing and leakage policies

A **carbon tax** or **emissions trading scheme** (ETS) can increase the economic viability of a CCUS project by either avoiding a fee (as in the case of a carbon tax) or through the selling of credits (as in the case of an ETS). As shown in Chapter 4, carbon prices between USD 40-60/t $CO_2$ are required for CCUS-based routes to breakeven with unabated routes for high-concentration applications, and between USD 80-170/t $CO_2$ for diluted applications.

As shown in Chapter 2, carbon pricing programmes have been in place for years, but have played a relatively minor role in incentivising the CCUS projects in operation today. Low and often volatile $CO_2$ prices are not enough to incentivise long-term investment in CCUS projects. Coupled with policies to reduce the high capital costs of projects, sustained high and predictable carbon prices send a signal to investors that can channel funding into projects in the long-term. For example, Canada's federal carbon pricing benchmark is set to gradually increase from CAD 65 Canadian dollars (USD 50) per tonne of $CO_2$-equivalent in 2023 to CAD 170 (USD 130) per tonne in 2030.

The story is slightly different in voluntary carbon markets, where high prices are incentivising investment in CDR technologies such as direct air capture and storage (DACS). As highlighted in Chapter 3, in the absence of clarity on CDR options in compliance markets, companies and emitters have been turning to voluntary carbon markets to purchase CDR credits. Companies are using these voluntary markets to meet their growing net zero commitments, and voluntary markets are fuelling most DACS projects today. As CDR technologies gain increased attention from both the public and private sectors, specific considerations will be needed to incorporate them into government-led compliance markets (see more in International Collaboration).

For jurisdictions with a carbon pricing system, low-emissions products can be protected against emission-intensive and cheaper imported goods by regulations such as a **carbon leakage policy**. One such example of a carbon leakage policy is a carbon border tax, also referred to as a carbon border adjustment mechanism (CBAM). Under this policy, an import tariff based on the carbon price is placed on carbon-intensive goods. By assigning an import tariff to these goods, this policy aims to level the playing-field with imports from other jurisdictions with less stringent emissions regulations and reduce the risk of companies leaving the carbon pricing jurisdiction (otherwise known as carbon leakage). It is crucial that the policy is designed in such a way that it promotes a just energy transition and continues to facilitate international trade. Negotiations with other countries will be a key aspect in this regard in order to align reporting requirements and prevent potential high compliance costs. The European Union applied the transitional phase of its CBAM in October 2023, and other countries (such as the United

States, Canada, the United Kingdom and Japan) have considered or are currently considering a similar policy.

### Structured revenue streams

A lack of revenue streams for CCUS projects directly impacts their economic viability. Based on successful policies in other sectors, two approaches are being used today to fill this revenue stream gap: a **regulated asset base** (RAB) model, and a **contract-for-difference** (CfD) or **carbon contract-for-difference** (CCfD) model. The United Kingdom is testing both approaches for different parts of the value chain.

The RAB model has been useful in supporting the build-out of network infrastructure in the energy sector, such as for electricity grids and oil and natural gas pipelines, and could now work for $CO_2$ transport and storage infrastructure. Under the RAB, a company acts as a manager for public infrastructure: it owns, invests in and operates infrastructure assets. In return, the government provides an opportunity for the company to recover its investments by establishing a set rate of return.

The contracts-for-difference model has been used as a means to increase the deployment of large-scale renewable energy projects, and could be applied to $CO_2$ capture projects as a way to provide revenue certainty. Under a CfD or CCfD, payments are made to CCUS projects based on the difference between the "reference price" (e.g. the price of electricity for a CfD or the carbon price for a CCfD) and a "strike price" (an amount previously agreed upon by the government and the project). Projects receive payments when the reference price is below the strike price, and inversely, when the reference price exceeds the strike price, the project must pay the government the prevailing difference.

## International collaboration can address cross-cutting areas

It is clear that no one country can accomplish large-scale CCUS deployment across multiple applications on their own. In order to reach global net zero emissions by 2050, a truly global effort on CCUS deployment needs to be on the agenda. International collaboration on CCUS can cut across several areas, including **innovation**, **cross-border storage of $CO_2$**, **CDR considerations** and deploying CCUS in **emerging markets and developing economies** (EMDEs).

### Innovation

The technology maturity of CCUS varies considerably by sector and application. Several technologies in $CO_2$ capture, transport, utilisation and storage are already deployed at large scale, but in other applications – including those that hold the promise of better performance and lower unit costs – further development is required.

As shown in Chapter 4, applications which are mature today are also not necessarily the ones consistent with a net zero energy system (e.g. capture on natural gas processing plants). Indeed, around three-quarters of capture capacity by 2050 in the NZE Scenario relies on technologies and applications that are still at demonstration or prototype scale. As such, governments should focus innovation efforts on applications that are still at demonstration or prototype scale. These innovation gaps need to be addressed with urgency to ensure that the technologies and applications are in place for large-scale roll-out after 2030.

Of course, cost reduction efforts such as **research, development and demonstration (RD&D) funding** are a core part of a government's toolkit for advancing CCUS innovation. Efforts should focus on technologies with a low technology readiness level (TRL) that are relevant to reach net zero emissions by 2050, such as CDR technologies and applications in heavy industry. Governments can encourage diversity and competition within RD&D funding as to not lock in certain solutions.

Governments are in a unique position to advance innovation, and maintaining **open collaboration on the international level** is necessary in order to ensure that the gains are shared equally. Countries with smaller RD&D budgets can benefit from increased international collaboration and knowledge-sharing. Existing platforms and initiatives, such as Mission Innovation, the Clean Energy Ministerial CCUS Initiative, and the Accelerating CCUS Technologies (ACT) programme can provide an important foundation for RD&D collaboration.

In addition to these initiatives, individual governments can facilitate technology co-development opportunities to funnel innovation to EMDEs. Existing **foreign direct investment** programmes can provide an avenue to facilitate technology co-development in EMDEs.

## Cross-border storage of $CO_2$

As shown in Chapters 1 and 3, CCUS projects in development now increasingly follow a ''many-to-many'' deployment model, where capture projects are developed as part of CCUS hubs that consist of shared transport and storage infrastructure connecting multiple emitters. When $CO_2$ is captured in one country and stored in another, this can trigger international obligations under the **London Protocol**.

According to the International Maritime Organization (IMO), contracting and non-contracting parties to the Protocol are required to co-operate to ensure information-sharing on the characterisation of the geological formation, storage integrity and potential migration and leakage pathways, among other areas.

### Obligations under the London Protocol

| London Protocol status of country capturing $CO_2$ for export | | London Protocol status of country receiving $CO_2$ for offshore storage: Contracting party | London Protocol status of country receiving $CO_2$ for offshore storage: Non-contracting party |
|---|---|---|---|
| | Contracting party (CP) | CPs must deposit a declaration of provisional application of the 2009 amendment with the IMO. CPs must establish an agreement or arrangement that includes "confirmation and allocation of permitting responsibilities, consistent with the provisions of the protocol and other applicable international law". This includes reference to the $CO_2$ specific guidelines' conditions related to the composition of $CO_2$ streams and $CO_2$ storage permitting. The IMO must be notified of these agreements or arrangements. | The exporting CP is accountable for compliance with the provisions of the protocol. The CP must establish an agreement or arrangement with the non-CP that, at a minimum, provides the same environmental protections as if the $CO_2$ were being stored by a CP. This includes the issuing of permits and permit conditions. In the case of a breach of the agreement or arrangement by the non-CP, the CP should "engage in consultations to rectify". In the case of a "significant ongoing breach", the CP is required to "terminate the export". |
| | Non-contracting party (non-CP) | CPs must establish an agreement or arrangement with the non-CP and notify the IMO of this. CPs must ensure that the $CO_2$ received is "overwhelmingly" comprised of $CO_2$ and that the exporting country demonstrates appropriate consideration of incidental associated substances in the $CO_2$ stream, with treatment if needed. | Not governed by the protocol; may be subject to United Nations Convention on the Law of the Sea. |

Source: IEA (2022), Legal and Regulatory Frameworks for CCUS

## Carbon dioxide removal considerations

To date, regulations tend to focus on emission *reduction* and not *removal*. As noted earlier, strong demand in voluntary carbon markets (VCMs) for CDR options is driving much of the interest seen today. Likewise, governments are considering how to incorporate CDR technologies in existing regulations, such as carbon pricing programmes.

One of the main challenges for governments is to define what a high-quality CDR option looks like, and initial attempts are emerging. This is based on several criteria: **quantification** (what is a reasonable deployment level), **additionality** (is the CDR approach additional to already ongoing efforts), **permanence** (how long will the $CO_2$ be sequestered), **sustainability** (what are the associated land and water requirements) and **negativity** (is the CDR approach carbon negative). Robust measurement, reporting and verification (MRV) mechanisms are needed to make sure CDR approaches are indeed providing climate benefits. MRV mechanisms for CDR will be key to incorporating high-quality CDR options into carbon pricing programmes, also called compliance markets.

The first methodologies for claiming carbon credits through VCMs are emerging through initiatives such as Puro.earth and CCS+. Puro.earth's Puro Standard was the first carbon removal standard for CDR technologies in the VCM. Climeworks and Carbfix, who are jointly developing the Orca DACS project, announced their intention to work with Puro.earth in certifying removal credits. The CCS+ Initiative aims to develop methodologies for issuing credits from CCUS activities (including CDR) and make them publicly available under Verra's Verified Carbon Standard. Although these methodologies apply only to issuance of credits in VCM, the Supervisory Body of the Article 6.4 mechanism of the Paris Agreement may consider them for approval or as a basis for further methodology development.

Public initiatives are also starting. The United Kingdom's Greenhouse Gas Removal business model proposal is defining criteria for a "negative emission" and principles that will guide the government's approach to MRV of removal technologies. In addition, the Carbon Removal Certification Framework in the European Union proposes to establish a regulation to facilitate high-quality removals based on four overarching criteria for which detailed methodologies will be developed: quantification, additionality and baselines, long-term storage, and sustainability.

As more countries and regions start to develop their own definitions, there is a strong need for international alignment, in both voluntary and compliance markets. International initiatives, such as the Mission Innovation (MI) CDR Mission, are working to develop certification and accounting standards. In 2022, the initiative released an action plan that identified MRV of removals as a top-priority area and called for the creation of a new "CDR MRV working group" within the MI CDR sub-mission.

## Emerging markets and developing economies

As shown in Chapter 1, the relatively low number of CCUS projects in development in EMDEs represents a major hurdle to achieve net zero emissions, given that EMDEs have large stocks of young emissions-intensive power plants and industrial facilities. While around one-third of $CO_2$ capture capacity currently in operation is located in EMDEs, this increases to approximately 50% by 2030 under the NZE Scenario. Increasing CCUS deployment in EMDEs can not only help some address their climate mitigation goals, but also work to achieve energy security and economic growth outcomes.

In the IEA CCUS Handbook on $CO_2$ Storage Resources and Their Development, we put forward a checklist for governments, particularly in EMDEs, that are interested in getting started on developing their $CO_2$ storage resources. This list is centred around six key points (national CCUS focal point, international support,

$CO_2$ storage assessment project team, national human capacity, data, and $CO_2$ storage assessment) and offers recommendations on the next steps.

In practice, most EMDEs will not be able to complete these tasks on their own, pointing to a vital need for **international support**. Mobilising capital and knowledge-sharing on a large scale will require a dramatic increase in the role of the private sector, and an enhanced role for international and development finance institutions will be critical to catalyse this investment.

For example, **concessional** or **climate finance** can be used strategically to mobilise private capital in support of CCUS. Concessional funds can include guarantees, senior or subordinated debt or equity, performance-based incentives, interest rate or swap cost buydowns, viability gap funding or other investment grants. **Sustainable debt** could also help to fund CCUS investment. While green bonds based on use of proceeds may not be available to all projects, performance-based instruments could facilitate CCUS investments, based on their emissions reduction potential. China updated its green bond standards to include CCUS in 2020.

**Multilateral development banks** have played an important role in supporting the development of enabling environments for CCUS in EMDEs through trust funds. For example, the World Bank CCS Trust Fund, funded by the United Kingdom and Norway, was established in 2009 and has allocated over USD 55 million to CCUS programmes in a dozen countries and regions. In addition, the Asian Development Bank's CCS Fund, which has since closed, was established in 2009 to support storage resource assessments, CCUS piloting and demonstration in Southeast Asia and China.

Unless a new instrument is established – with the World Bank's fund set to close in 2024 – there will no longer be any dedicated multilateral development bank funding instrument to support the development of CCUS-enabling environments or piloting. This represents a major gap in international funding support for CCUS in EMDEs, as most typically rely on some level of multilateral development funding to perform technical assistance studies that underpin the development of legal and regulatory frameworks and CCUS policies. Given that in the NZE Scenario approximately one-half of all $CO_2$ capture capacity is located in EMDEs by 2030, up from one-third today, further and immediate support is needed. **Grants** and **loans** from development and climate finance institutions, emissions credit mechanisms and climate-related debt financing could all be applied to CCUS projects.

Some other existing multilateral funding instruments for EMDEs could apply to CCUS, such as the Green Climate Fund; however, no CCUS activities have been funded to date.

# A policy toolkit

Building a commercial market for CCUS is no easy task: it requires addressing multiple economic, lead time, innovation and complexity challenges. However, these challenges are not unsurmountable, and overcoming them is entirely possible with the right policy environment and investment from industry.

Governments are uniquely positioned to create this policy environment, and how they approach building it will depend on several institutional, economic and political factors. Whether the approach is through **incentives or penalties** that try to guide company investment, **sharing cost allocation** to provide greater revenue certainty, or **fully controlling** aspects of deployment through state-owned enterprises, governments can employ different approaches that fit their specific needs.

To fine-tune their approach, governments have at their disposal a set of policy tools to tackle the overarching challenges to CCUS deployment. These tools form a broader toolkit that comprises **enabling legislation and rules**, **cost reduction measures**, **regulation of industrial activities**, **strategic signalling** and **revenue support**.

Governments can use these policy tools to create the conditions necessary for sustained investment, but at the end of the day it is the responsibility of industry to take the next step forward and push forward CCUS into a viable and sustainable commercial market.

## A policy toolkit for CCUS

### Policy approaches for CCUS deployment

There is no one single approach to building a commercial market for CCUS. Various approaches should be thought of as existing on a spectrum: **incentive- or penalty-based**, **shared cost allocation** and **full control** approach.

Institutional, economic and political factors will influence what part of the CCUS policy spectrum a country may end up on, and countries may move along the spectrum as these factors change and as the domestic market for CCUS matures. Where a country sits on the spectrum may impact the types of policy tools that it chooses to use.

**Approaches**

**Incentive- or penalty-based approach**

Policies to influence how a private company will make its investment decisions. This is either done with **incentives** (e.g. grants, loans or tax credits) to private companies to deploy a certain technology or adopt a certain practice, or with **penalties** (e.g. taxes or fees) for not complying with regulations.

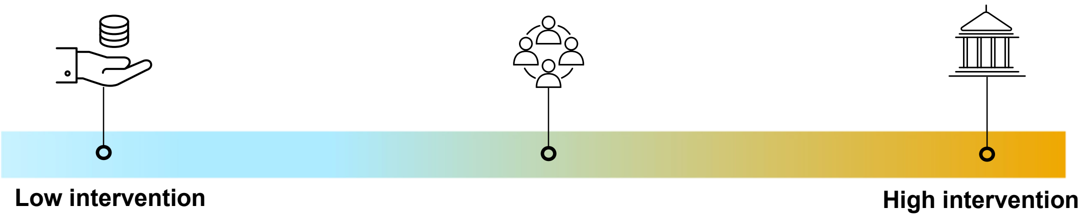
**Shared cost allocation approach**

Economic parameters govern the cost and revenue structures of a company, which is shared between the public and private sectors. This approach may be well suited for large infrastructure endeavours, such as the development of a $CO_2$ transportation and storage network.

**Full control approach**

Instead of solely relying on the private sector to develop a market, this approach leans on state-owned enterprises to finance, build, own and operate projects. It may still rely on some level of private sector involvement, whether it is through jointly developing projects, as a customer or as an investor.

**Level of government intervention**




### Policy toolkit to address CCUS challenges

Governments have several policy tools to address challenges to CCUS deployment. It is important that these tools work together to tackle **economic viability**, **lead time**, **innovation** and **complexity** challenges.

Whatever tools a government chooses to employ will be unique to that country, but it is vital that the tools are effective and efficient, setting up a viable and sustainable commercial market for CCUS that attracts investment and retains it over the long term.

**Challenges**

**Economic viability**

Absent any policy support, the economic viability of a CCUS project is a major barrier to wide-scale deployment. High costs and a lack of revenue streams for projects directly impact a project's economic viability.

**Lead times**

Lead times (i.e. the total time required between a project's conception and commissioning) currently average around six years. Reaching net zero goals hinges on cutting these lead times.

**Innovation gaps**

The technology maturity of CCUS varies considerably by technology type and application. Technologies which are mature today are also not necessarily the ones consistent with a net zero energy system.

**Project complexity**

The shift to a hub model means a complex project structure, with implications for risk, timing and co-ordination. Special considerations are also needed for carbon dioxide removal technologies.

**Policy tools**

Economic viability:
- ❑ **Grants, tax credits, loans**
- ❑ **State-owned enterprises**
- ❑ **Carbon pricing and leakage policy**
- ❑ **Public procurement**
- ❑ **Low-emissions mandates**
- ❑ **(Carbon) contracts-for-difference**
- ❑ **Regulated asset base**
- ❑ **Emerging market and developing economy considerations:** concessional finance, sustainable debt, multilateral funding instruments

Lead times:
- ❑ **One-stop shop for permitting**
- ❑ **Clear approval timelines**
- ❑ **Internal regulatory capacity**
- ❑ **Precompetitive resource assessments**
- ❑ **Data sharing and transparency**
- ❑ **Community engagement requirements**

Innovation gaps:
- ❑ **Research, development and demonstration**
- ❑ **Platforms for international co-operation**
- ❑ **Foreign direct investment for technology co-development**

Project complexity:
- ❑ **Long-term liability legislation**
- ❑ **Competitive solicitations for hubs**
- ❑ **One-off backstop agreements for first movers**
- ❑ **London Protocol specifications**
- ❑ **Definition of high-quality removals**
- ❑ **Monitoring, reporting and verification mechanisms**

# General annex

## Annex A: Large-scale CCUS operating projects, 2023

### Large-scale CCUS operating projects, 2023

| Project name | Country | Project type | Construction type | Sector | Operation year | Estimated capacity (Mt/yr) |
|---|---|---|---|---|---|---|
| Abu Dhabi CCS Phase 1: Emirates Steel Industries | United Arab Emirates | Full-chain | Retrofit | Iron and steel | 2016 | 0.8 |
| Alberta Carbon Trunk Line (ACTL) (ALB) | Canada | Transport | New | $CO_2$ transport | 2020 | 14.6 |
| Arcelor LanzaTech Carbalyst (Steelanol) Ghent | Belgium | CCU | Retrofit | Iron and steel | 2022 | 0.1 |
| Arkalon $CO_2$ Compression Facility (KS) | United States | Full-chain | Retrofit | Bioethanol | 2009 | 0.3 |
| Bonanza BioEnergy CCUS (KS) | United States | Full-chain | Retrofit | Bioethanol | 2012 | 0.2 |
| Boundary Dam CCS (SASK) | Canada | Full chain | Retrofit | Power (coal) | 2014 | 1.0 |
| Century plant (TX) | United States | Full-chain | New | Natural gas processing | 2010 | 4.3 |
| Changling Gas plant /Jilin Oil Field $CO_2$-EOR Full-scale (Jilin) | China | Full-chain | New | Natural gas processing | 2018 | 0.6 |
| China Energy Taizhou power (Jiangsu) | China | Capture | Retrofit | Power (coal) | 2023 | 0.5 |
| China Energy Guohua Jinjie Power (Shaanxi) | China | Full-chain | Retrofit | Power (coal) | 2021 | 0.2 |
| Climeworks Orca | Iceland | Full-chain | New | Direct Air Capture | 2021 | 0.004 |
| Clive $CO_2$-EOR (ACTL) (ALB) | Canada | Storage | New | $CO_2$ EOR | 2020 | 1.1 |
| CNOOC Enping offshore CCS (Hong Kong) | China | Full-chain | New | Oil and gas extraction | 2023 | 0.3 |
| Coffeyville fertiliser Plant (KS) | United States | Full-chain | Retrofit | Fertiliser | 2013 | 0.9 |
| Core Energy $CO_2$-EOR South Chester plant (MI) | United States | Full-chain | Retrofit | Natural gas processing | 2003 | 0.4 |
| Enid fertiliser (OK) | United States | Full-chain | New | Fertiliser | 1982 | 0.7 |

| Project name | Country | Project type | Construction type | Sector | Operation year | Estimated capacity (Mt/yr) |
|---|---|---|---|---|---|---|
| Global thermostat headquarters plant (CO) | United States | Capture | New | Direct Air Capture | 2023 | 0.001 |
| Gorgon CCS | Australia | Full-chain | New | Natural gas processing | 2019 | 4.0 |
| Great Plains Synfuel Plant (ND) Weyburn-Midale (SK) | United States | Full-chain | Retrofit | Coal-to-gas | 2000 | 3.0 |
| Horizon $H_2$ capture tailings CCS (ALB) | Canada | CCU | Retrofit | Refining | 2009 | 0.4 |
| Illinois Industrial Carbon Capture and Storage (IL) | United States | Full-chain | Retrofit | Bioethanol | 2017 | 0.5 |
| Jiling Petrochemical CCUS (Nanjing refinery) (Jiangsu) | China | Full-chain | Retrofit | Coal-to-liquids | 2023 | 0.1 |
| Karamay Dunhua methanol plant (Xinjiang) | China | Full-chain | Retrofit | Chemicals (methanol) | 2015 | 0.1 |
| Labarge Shute Creek Gas Processing Plant 2010 expansion (WY) | United States | Full-chain | Extension | Natural gas processing | 2010 | 3.5 |
| Labarge Shute Creek Gas Processing Plant original (WY) | United States | Full-chain | New | Natural gas processing | 1986 | 3.5 |
| Lost Cabin Gas Plant extension (WY) | United States | Full-chain | Retrofit | Natural gas processing | 2013 | 0.9 |
| Mikawa Power Plant BECCS Fukuoka Prefecture | Japan | Capture | Retrofit | Power (bioenergy) | 2020 | 0.2 |
| MOL Szank field $CO_2$ EOR | Hungary | Full-chain | Retrofit | Natural gas processing | 1992 | 0.2 |
| NWR $CO_2$ Recovery Unit (Sturgeon Refinery) (ACTL) (ALB) | Canada | Capture | New | Refining | 2020 | 1.3 |
| PCS Nitrogen-Geismar plant (LA) | United States | Full-chain | Retrofit | Fertiliser | 2013 | 0.3 |
| Petra Nova Carbon Capture (TX) | United States | Full-chain | Retrofit | Power (coal) | 2016-2020, 2023 | 1.4 |
| Petrobras Santos Basin pre-salt oilfield CCS | Brazil | Full-chain | New | Natural gas processing | 2013 | 8.7 |
| Qatar LNG | Qatar | Full-chain | New | Natural gas processing | 2019 | 2.1 |
| Quest (ALB) | Canada | Full-chain | Retrofit | Refining | 2015 | 1.1 |
| Red Trail Energy BECCS Project (ND) | United States | Full-chain | Retrofit | Bioethanol | 2022 | 0.2 |
| Shell heavy residue gasification CCU - Pernis refinery | Netherlands | CCU | Retrofit | Refining | 1997 | 0.4 |
| Sinopec Nanjing Chemical Industries CCUS Cooperation Project (Jiangsu) | China | Full-chain | Retrofit | Chemicals (other) | 2021 | 0.2 |

| Project name | Country | Project type | Construction type | Sector | Operation year | Estimated capacity (Mt/yr) |
|---|---|---|---|---|---|---|
| Sinopec Qilu Petrochemical Shengli (Shandong) | China | Full-chain | Retrofit | Fertiliser | 2022 | 1.0 |
| Sleipner | Norway | Full-chain | New | Natural gas processing | 1996 | 1.0 |
| Snøhvit $CO_2$ capture and storage | Norway | Full-chain | New | Natural gas processing | 2008 | 0.7 |
| Terrell Natural Gas Processing Plant (former Val Verde) (TX) | United States | Full-chain | New | Natural gas processing | 1972 | 0.5 |
| Uthmaniyah $CO_2$-EOR demonstration | Saudi Arabia | Full-chain | Retrofit | Natural gas processing | 2015 | 0.8 |
| Valero Port Arthur Refinery (TX) | United States | Full-chain | Retrofit | Refining | 2013 | 0.9 |
| WCS Redwater $CO_2$ Recovery Unit (formerly Nutrien) (ACTL) (ALB) phase 1 | Canada | Capture | Retrofit | Fertiliser | 2019 | 0.3 |

Note: Large-scale refers to a capture capacity equal to or above 100 000 t $CO_2$/yr (or 1 000 for direct air capture applications).
Source: IEA (2023), CCUS Projects Database.

# Annex B: Principal capture technologies

**Chemical absorption** of $CO_2$ is a common process operation based on the reaction between $CO_2$ and a chemical solvent (such as compounds of ethanolamine). This operation is usually performed using two columns, one for the absorption and the other operating at a higher temperature, releasing pure $CO_2$ and regenerating the chemical solvent for further operation. Chemical absorption using amine-based solvents is the most advanced $CO_2$ separation technique (TRL 7-11).[19] It has been widely used for decades and is currently applied in a number of small- and large-scale projects worldwide in power generation, fuel transformation and industrial production.

**Physical separation** of $CO_2$ is based on either adsorption, absorption, cryogenic separation, or dehydration and compression. Physical adsorption makes use of a solid surface (e.g. activated carbon, alumina, metallic oxides or zeolites), while physical absorption makes use of a liquid solvent (e.g. Selexol or Rectisol). After capture by means of an adsorbent, $CO_2$ is released by increasing temperature (temperature swing adsorption [TSA]) or reducing pressure (pressure swing adsorption [PSA] or vacuum swing adsorption [VSA]). Physical separation is currently used mainly in ammonia, methanol, and high value chemical production, and coal with CCUS processing, with numerous large plants in operation (TRL 7-9). They typically employ proprietary solvents, VSA or cryogenic separation techniques.

**Oxy-fuel separation** involves the combustion of a fuel using nearly pure oxygen and the subsequent capture of the $CO_2$ emitted. Because the flue gas is composed almost exclusively of $CO_2$ and water vapour, the latter can be removed easily by means of dehydration to obtain a high-purity $CO_2$ stream. Typically, oxygen is produced commercially via low-temperature air separation, which is energy-intensive. Lowering the energy consumption of this step and of the overall oxy-fuel process are, therefore, key factors in reducing capture costs. Advanced concepts with potential for cost reduction include oxy-fuel gas turbines (used within supercritical $CO_2$ power cycles) and pressurised oxy-fuel $CO_2$ capture, both of which make more efficient use of materials and are thus potentially cheaper to build and operate. The technology is currently at the large prototype or pre-demonstration stage (TRL 5 to 7). A number of projects have been completed in coal-based power generation and in cement production. While in conventional thermal power plants, flue gas or steam is used to drive one or multiple turbines,

[19] For further information on the IEA Technology Readiness Level (TRL) scale, please refer to the ETP Clean Energy Technology Guide.

in **supercritical $CO_2$ power cycles**, supercritical $CO_2$ (i.e. $CO_2$ above its critical temperature and pressure) is used instead. Supercritical $CO_2$ turbines typically use nearly pure oxygen to combust the fuel, in order to obtain a flue gas composed of $CO_2$ and water vapour only (TRL 5-6).

**Membrane separation** is based on polymeric or inorganic devices (membranes) with high $CO_2$ selectivity, which let $CO_2$ pass through but act as barriers to retain the other gases in the gas stream. Their TRLs vary according to the fuel and application. In natural gas processing, they are mainly at the demonstration stage (TRL 5-7). Membranes for $CO_2$ removal from syngas and biogas are already commercially available, while membranes for flue gas treatment are currently under development.

**Calcium looping** is a technology that involves $CO_2$ capture at a high temperature using two main reactors. In the first reactor, lime (CaO) is used as a sorbent to capture $CO_2$ from a gas stream to form calcium carbonate ($CaCO_3$). The $CaCO_3$ is subsequently transported to the second reactor where it is regenerated, resulting in lime and a pure stream of $CO_2$. The lime is then looped back to the first reactor. Calcium looping technologies, currently at TRL 7, have been tested, mostly at the pilot plant scale, for coal-fired fluidised bed combustors and cement manufacture.

**Chemical looping** is a similar two-reactor technology. In the first reactor, small particles of metal (e.g. iron or manganese) are used to bind oxygen from the air to form a metal oxide, which is then transported to the second reactor where it reacts with fuel, producing energy and a concentrated stream of $CO_2$, regenerating the reduced form of the metal. The metal is then looped back to the first reactor. Chemical looping technologies have been developed by academia, research organisations and several companies, including manufacturers operating in the power sector. This has led to the development and operation of numerous pilot projects (TRL 4-5).

**Direct separation** involves the capture of $CO_2$ process emissions from cement production by indirectly heating the limestone using a special calciner (TRL 6-7). This technology strips $CO_2$ directly from the limestone, without mixing it with other combustion gases, thus considerably reducing energy costs related to gas separation.

# Annex C: CCUS cost metrics

The **levelised cost of capture** (LCC) calculates the average cost incurred per unit of $CO_2$ captured over the lifetime of a capture project. It includes capital and operational expenses associated with capturing $CO_2$ from a point source, and can be used to compare different CCUS approaches within and across sectors. This metric can be added to the levelised cost of transporting and storing (or utilising) $CO_2$ to calculate the economic impacts of implementing CCUS in a given sector (**levelised cost of capture, transport and storage (T&S)**, or **capture, transport and utilisation**).

$$LCCUS\ (USD\ per\ tonne\ CO_2\ captured) = LCC +\ CO_2\ T\&S\ cost$$

The **levelised cost of $CO_2$ removal (LCR)** refers to the economic expenditure needed to deliver net $CO_2$ removal from the atmosphere. This metric differs from the levelised cost of capture in the way it includes all lifecycle $CO_2$ emissions to calculate the technology's net removal potential. Evaluating the cost of $CO_2$ removal is essential in assessing the economic feasibility of different carbon removal strategies.

$$LCR\ (USD\ per\ tonne\ CO_2\ removed) = LCC\ x\ \frac{CO_2\ captured}{CO_2\ captured - CO_2\ emitted}$$

Metrics such as the **levelised cost of electricity (LCOE), hydrogen (LCOH) or materials (LCOM)**, calculate the lifetime costs of producing a certain end-product with a given technology, with or without CCUS. They calculate the investment and operation costs associated with the entire production process, in addition to capturing, transport and storing the $CO_2$.

The **levelised cost of $CO_2$ avoided (LCCA)** quantifies the investment and operational costs required to deliver a certain amount of net $CO_2$ emissions reduction. This metric differs from the LCC by considering any additional $CO_2$ emissions incurred by the implementation of a decarbonisation solution. In the case of CCUS this can be emissions associated with capturing, transporting or storing $CO_2$. With this metric the competitiveness of CCUS projects relative to other emission reduction strategies can be assessed. However, this metric is heavily affected by the baseline, which needs to be carefully selected and defined.

$$LCCA = \frac{Levelised\ cost\ (plant\ with\ capture) - Levelised\ cost\ (plant\ without\ capture)}{CO_2\ emissions\ (plant\ without\ capture) - CO_2\ emissions\ (plant\ with\ capture)}$$

# Annex D: Dashboard notes

## Capture

## Project pipeline

Data is sourced from the IEA CCUS Projects Database. The database available for download contains projects updates as of February 2023. This report relies on an internal version of the database with project updates as of Q2 2023, with the exception of major project updates which include projects (re)entering operation or construction, which are included up to October 2023.

### Capture

Includes commercial-scale projects with a capture capacity over 100 000 t per year (or 1 000 for direct air capture applications) with an announced operating year by 2030. Capture projects for $CO_2$ use are included as long as $CO_2$ is used in fuels, chemicals, polymers, building materials, or for yield boosting. Within planned industrial clusters, only identified $CO_2$ capture projects are included (not the full potential capture capacity of industrial clusters for which capture sources are not specified). ''Under construction'' also includes projects which have reached a final investment decision (FID) and for which construction is imminent. Hydrogen only includes merchant hydrogen and ammonia plants.

### Storage

Storage includes both dedicated $CO_2$ storage and $CO_2$-enhanced oil recovery (EOR). While most of the $CO_2$ injected for EOR is retained in the reservoir over the life of the project, additional monitoring and verification is required to confirm that the $CO_2$ has been permanently stored.

### Transport

Current estimate of pipeline proposed in km is based on announced projects with disclosed distances only.

## Technology readiness

Data from the IEA Clean Energy Technology Guide, 2023.

FCC = fluid catalytic cracker; FT = Fischer-Tropsch; L-DAC = liquid direct air capture; PC = pulverised combustion; Pre-C = pre-combustion; SMR = steam methane reforming; S-DAC = solid direct air capture.

# Costs

## Capture

Levelised cost of capture for sectors that have not been demonstrated at scale yet (particularly diluted and air capture) reflect nth-of-a-kind costs, excluding the unique cost premiums typically associated with first- or second-of-a-kind projects. Main assumptions include: cost of electricity: USD 32-116/MWh; cost of fuel: USD 4-14/GJ (natural gas), USD 2-7/GJ (coal), USD 7-9/GJ (biomass); plant lifetime (years): 40 (coal, biomass), 35 (gas), industrial facilities and hydrogen (25), DAC facility (10-25); capacity factor: 85% (power), 95% (hydrogen, industry, fuel transformation, DAC); capture rates: partial (60%), all (90%), hydrogen and ammonia (93%); discount rate: 8%. Capture rates are for the overall plant for power, hydrogen and cement, and for a specific stream for the steel blast furnace, refinery fluid catalytic cracker, natural gas processing plant and biofuel plant. For hydrogen, DAC, fuel transformation and industry applications, heat is assumed to be provided by a natural gas-fuelled auxiliary boiler, and electricity from the grid. Costs expressed in year-2022 dollars.

Sources: Power: IEA (2023), NETL (2022), IEAGHG (2019); Cement: NETL (2022), IEAGHG (2013), CEMCAP (2015); Steel: NETL (2022), IEAGHG (2013); Hydrogen: NETL (2022), IEAGHG (2019), IEAGHG (2017), data from The Hydrogen Council (2021); Ammonia: EFI (2023), NETL (2022), IEA (2021); Biofuels: data from IEA Bioenergy (2019), IEAGHG (2021), DEA (2017) ; Natural gas processing: EFI (2023), NETL (2022); Refinery: EFI (2023), NETL (2022), IEAGHG (2017); DAC: Bloomberg (2021), IEAGHG (2021), IEA (2023), Oxy (2022).

## Storage

Assumptions for storage costs: costs expressed in year-2022 dollars.

Sources: US onshore and offshore storage cost curve: EPA (2021), Sleipner capital cost (Torp & Brown, 2005), Snøhvit capital cost (IEEFA, 2023), Quest capital cost (Alberta Department of Energy, 2021), Gorgon capital cost (Chevron, 2021).

Notes for project costs:

Snøhvit: A series of challenges resulted in the capital cost at the time of project commencement in 2008 being twice the original budget. During operation, salt precipitation, which is a common issue, impacted early injection rates. Snøhvit mitigated this by injecting a chemical solution. However, the pressure build-up in the Tubåen formation was mainly attributed to a limited reservoir volume and heterogeneities. As a result, it appeared unlikely that the Tubåen formation would be able to support the rate and volume of $CO_2$ injection required by the Snøhvit project over its lifetime. The new injection zone for Snøhvit incurred further mitigation costs in the capital expenditure.

Gorgon: around a quarter of the budget is attributed to drilling related costs (drilling of 19 new wells and remediation of 3 existing wells) and indirect costs including project management, FEED, commissioning, and additional logistics.

## Transport

Assumptions for transport costs: costs expressed in year-2022 dollars.

Sources: techno-economic costs for pipeline and shipping: Rubin et al. (2015), US DOE (2023), IEAGHG (2020), Quest transport unit cost (Alberta Department of Energy, 2021), Alberta Carbon Trunk Line unit cost (Alberta Carbon Trunk Line, 2022).

# Annex E: Regional and country groupings

**Advanced economies:** OECD regional grouping and Bulgaria, Croatia, Cyprus[20], Malta and Romania.

**Africa:** North Africa and sub-Saharan Africa regional groupings.

**Asia Pacific:** Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, The People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[21]

**Caspian:** Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

**Central and South America:** Argentina, Plurinational State of Bolivia (Bolivia), Bolivarian Republic of Venezuela (Venezuela), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay and other Central and South American countries and territories.[22]

**China:** Includes (The People's Republic of) China and Hong Kong, China.

**Developing Asia:** Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

**Emerging market and developing economies:** All other countries not included in the advanced economies regional grouping.

**Eurasia:** Caspian regional grouping and the Russian Federation (Russia).

[20] The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus issue". The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[21] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga and Vanuatu.

[22] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten (Dutch part), Turks and Caicos Islands.

**Europe:** European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Iceland, Israel[23], Kosovo, Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

**European Union:** Austria, Belgium, Bulgaria, Croatia, Cyprus,[24] Czech Republic (Czechia), Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

**IEA (International Energy Agency):** OECD regional grouping excluding Chile, Colombia, Costa Rica, Iceland, Israel, Latvia and Slovenia.

**Latin America and the Caribbean (LAC):** Central and South America regional grouping and Mexico.

**Middle East:** Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

**Non-OECD:** All other countries not included in the OECD regional grouping.

**Non-OPEC:** All other countries not included in the OPEC regional grouping.

**North Africa:** Algeria, Egypt, Libya, Morocco and Tunisia.

**North America:** Canada, Mexico and United States.

**OECD (Organisation for Economic Co-operation and Development):** Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom and United States.

**OPEC (Organization of the Petroleum Exporting Countries):** Algeria, Angola, Bolivarian Republic of Venezuela (Venezuela), Equatorial Guinea, Gabon, Iraq, Islamic Republic of Iran (Iran), Kuwait, Libya, Nigeria, Republic of the Congo (Congo), Saudi Arabia and United Arab Emirates.

[23] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[24] The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus issue". The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

**OPEC+:** OPEC grouping plus Azerbaijan, Bahrain, Brunei Darussalam, Kazakhstan, Malaysia, Mexico, Oman, Russian Federation (Russia), South Sudan and Sudan.

**Southeast Asia:** Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

**Sub-Saharan Africa:** Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Kingdom of Eswatini, Madagascar, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Uganda, Zambia, Zimbabwe and other African countries and territories.[25]

[25] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Mauritania, Sao Tome and Principe, Seychelles, Sierra Leone and Somalia.

# Abbreviations and acronyms

| | |
|---|---|
| ACCU | Australian Carbon Credit Units |
| ACT | Accelerating CCUS Technologies |
| ACTL | Alberta Carbon Trunk Line |
| AUD | Australian dollars |
| BECCS | Bioenergy with carbon capture and storage |
| BF-BOF | Blast furnace basic oxygen furnace |
| CAD | Canadian dollars |
| CaO | Calcium oxide (lime) |
| $CaCO_3$ | Calcium carbonate |
| CAPEX | Capital expenditure |
| CBAM | Carbon Border Adjustment Mechanism |
| CCfD | Carbon contract-for-difference |
| CCGT | Combined cycle gas turbine |
| CCS | Carbon capture and storage |
| CCU | Carbon capture and utilisation |
| CCUS | Carbon capture, utilisation and storage |
| CDR | Carbon dioxide removal |
| CEF | Connecting Europe Facility |
| CfD | Contract-for-difference |
| CIFIA | $CO_2$ Transportation Infrastructure Finance and Innovation Act |
| CNPC | China National Petroleum Corporation |
| COP | Conference of the Parties |
| $CO_2$ | Carbon dioxide |
| CP | Contracting party |
| DAC | Direct air capture |
| DACS | Direct air capture and storage |
| DoE | Department of Energy (United States) |
| DRI | Direct reduced iron |
| EBN | Energie Beheer Nederland |
| EGR | Enhanced gas recovery |
| EMDEs | Emerging markets and developing economies |
| EOR | Enhanced oil recovery |
| EPC | Engineering, procurement, construction |
| ETS | Emission trading system |
| EUDP | Energy Technology Development and Demonstration Programme |
| EWR | Enhanced water recovery |
| FCC | Fluid catalytic cracker |
| FEED | Front-end engineering and design |
| FID | Final investment decision |
| FOAK | First-of-a-kind |
| FT | Fischer-Tropsch |
| GHG | Greenhouse gas |
| $H_2$ | Hydrogen |

| | |
|---|---|
| HVC | High value chemical |
| IIJA | Infrastructure Investment and Jobs Act |
| IMO | International Maritime Organization |
| ITC | Investment Tax Credit |
| JOGMEC | Japan Organization For Metals and Energy Security |
| JV | Joint venture |
| LCC | Levelised cost of capture |
| LCOE | Levelised cost of electricity |
| LCOH | Levelised cost of hydrogen |
| LCOM | Levelised cost of material |
| LCR | Levelised cost of CO2 removal |
| LPO | Loan Programs Office |
| MI | Mission Innovation |
| MMV | Monitoring, measurement and verification |
| MRV | Measurement, reporting and verification |
| NDC | Nationally determined contribution |
| Non-CP | Non-contracting party |
| NSTA | North Sea Transition Authority |
| OEM | Original equipment manufacturer |
| OPEX | Operational expenditure |
| PC | Pulverised combustion |
| PSA | Pressure swing adsorption |
| PV | Photovoltaic |
| R&D | Research and development |
| RAB | Regulated asset base |
| RD&D | Research, development and demonstration |
| SMR | Steam methane reforming |
| SOE | State-owned enterprise |
| TRI | Transport and Storage Regulatory Investment |
| TRL | Technology Readiness Level |
| TSO | Transmission System Operators |
| UN | United Nations |
| UNIDO | United Nations Industrial Development Organization |
| VCM | Voluntary carbon market |
| VCS | Verified Carbon Standard |
| VSA | Vacuum swing adsorption |
| WACC | Weighted average cost of capital |

# Units of measure

| | |
|---|---|
| GJ | Gigajoule |
| Gt $CO_2$ | Gigatonne of carbon dioxide |
| GW | Gigawatt |
| GWh | Gigawatt hour |
| kW | Kilowatt |

| | |
|---|---|
| kWh | Kilowatt hour |
| MW | Megawatt |
| MWh | Megawatt hour |
| yr | year |

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