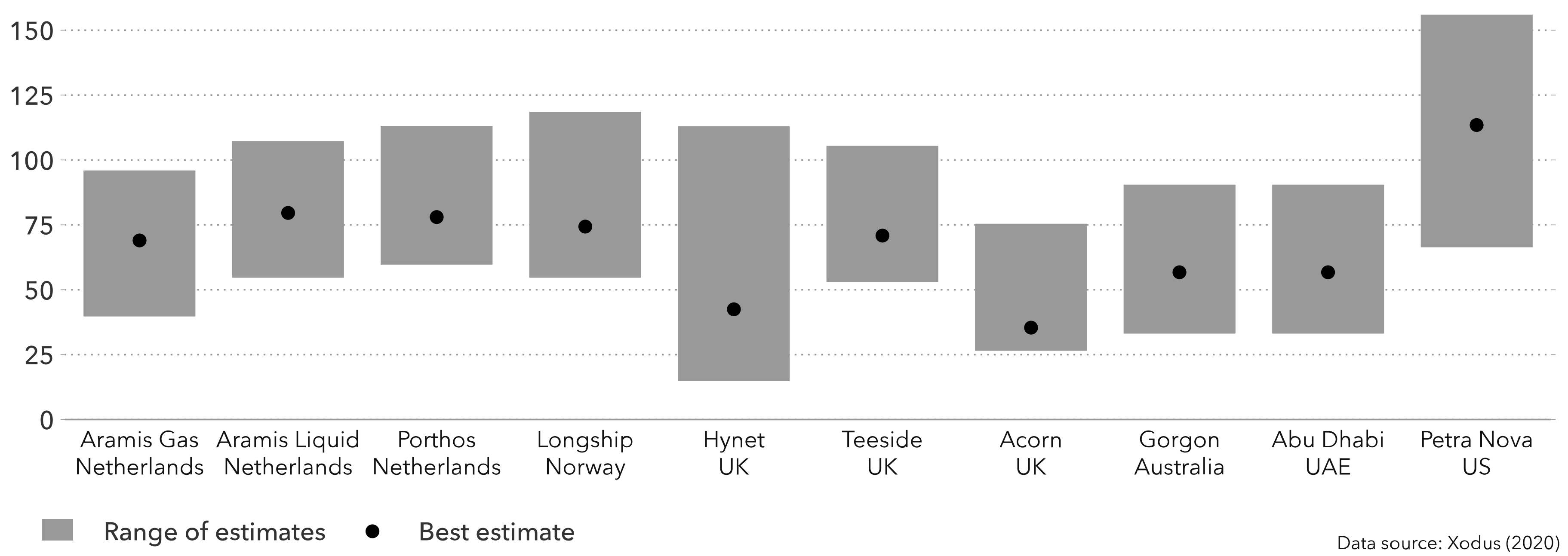
Pipeline transport benefits from economies of scale when mass flow rates increase, particularly in dense phase with higher fluid density when more CO_2 can be transported efficiently. While we anticipate a similar effect for ships, trains, and trucks, the need for additional vessels, railcars, or trucks would offset some of the advantages.

Reusing existing infrastructure such as natural gas pipelines can potentially reduce transport capital costs but could incur increased costs associated with inspection and requalification works.

FIGURE 2.2

Transport and storage tariff comparisons of major projects

Units: USD/tCO_2



Data source: Xodus (2020)

Storage

CO_2 storage costs include characterization and development work, drilling and operation of injection wells, and monitoring costs. Generally, there is less detailed cost analysis available for storage than for capture and transport. However, the key cost drivers are whether the site is onshore or offshore and whether it involves a depleted oil and gas field or a saline aquifer.

A recent EU review identified a cost range of USD 5-35/tCO_2 for storage in saline aquifers, with a lower cost range of USD 3-15/tCO_2 for storage in depleted oil and gas fields (EU Joint Research Centre, 2024) due to decreased characterization costs and potential to re-use infrastructure.

> Pipeline transport benefits from economies of scale when mass flow rates increase.

Earlier analysis by Zero Emissions Platform and the International Energy Agency (IEA) found that offshore storage, more common in Europe, carries significantly higher costs (1.5-3x) than onshore storage, which is more common in the US (IEA, 2020; Zero Emissions Platform, 2011).

Tariffs

When a third party operates transport and storage networks, the tariffs charged to the emitters are higher than the cost of the facilities themselves. In fact, these tariffs will include project contingencies, business model contingencies, the margin for the operators, and the inefficiencies for scale-up in the early phases of the project.

Energy consultancy Xodus has analysed transport and storage tariffs among the main large-scale CCS projects across the globe (Figure 2.2) and concluded that transport and storage tariffs would average around USD 74/tCO_2 (Xodus, 2022). This figure will vary between projects within Europe due to higher costs associated with CO_2 shipping, offshore storage, gas-phase pipelines, and transport through urbanized areas. In other regions, tariffs could be lower due to factors such as onshore storage, lower urbanization, and the widespread use of pipelines contributing to reduced costs.

Full-chain outlook

The costs of CCS vary widely between projects and a study is typically conducted at the beginning of a project to get a precise estimate. For simple onshore projects, like gas processing near storage locations, costs can be as low as USD 30/tCO_2, as seen with the Moomba project in Australia (Jacobs, 2024). However, capturing CO_2 from sources with lower concentrations and shipping it can quickly increase costs to the USD 100-300/tCO_2 range. In Asia, shipping alone can add around USD 100/tCO_2, depending on distance and scale (GCCSI, 2025).

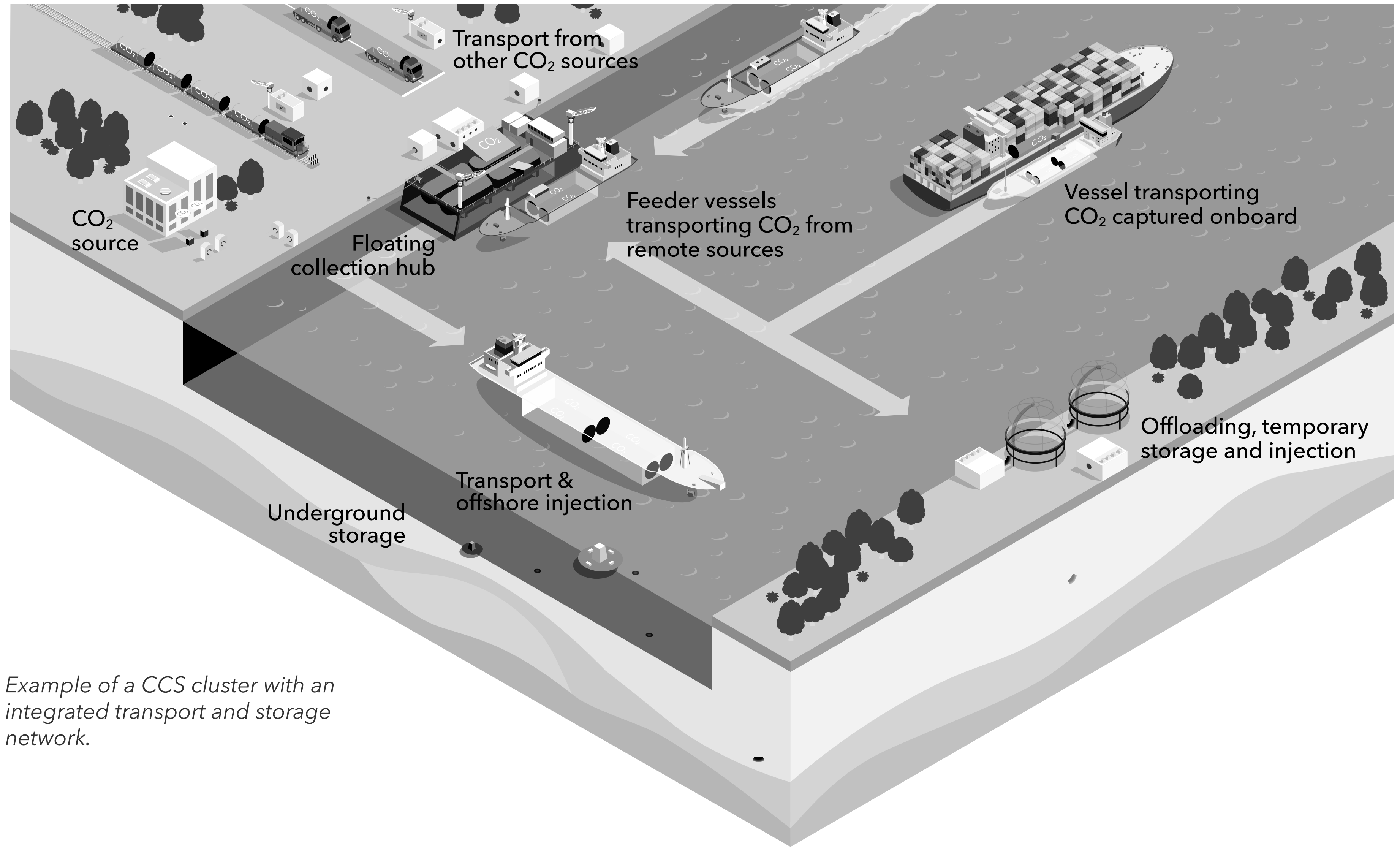
A horizon-scanning exercise undertaken as an IEAGHG study (Orchard et al., 2021) projected operational cost reductions by 2040 in the 20 to 30% range. These are likely to result from a combination of factors that include smarter materials, additive manufacturing, and more effective operations and maintenance due to the use of the Internet of Things, virtual reality, and artificial intelligence.

The main challenge globally is making CCS commercially viable. Carbon prices are generally not high enough to justify the investment without government support. While Europe might be an exception for some low-cost projects, government assistance is crucial to enable the private sector to invest the billions of dollars needed to achieve net-zero targets.

2.5 VALUE CHAIN

The CCS value chain encompasses three primary components: CO_2 capture, transport, and storage. Each segment is highly interdependent and requires significant coordination to ensure the seamless flow of operations.

The optimal value chain is determined by several considerations. These include storage requirements, CO_2 emitter and storage location and terrain, volumes, local regulations, and risk assessment.



Example of a CCS cluster with an integrated transport and storage network.

Among all the solutions deemed feasible, the choice of the infrastructure is primarily driven by cost efficiency, i.e. the practicable value chain that can move the CO_2 from emission sources to geological storage locations at minimum cost. Usually, each project requires its own dedicated assessment to identify the optimal solution.

There is a growing interest in the development of large-scale CCS clusters and integrated transport and storage networks that will enable multiple emitters to deliver their CO_2 in exchange for a tariff. Experienced operators then manage the transport and storage of the CO_2 captured at their facilities. Moreover, from an economic standpoint, CCS benefits remarkably from the scale effect, with larger volumes resulting in a significant reduction in the levelized cost (i.e. per tonne cost). This cluster approach not only drives the levelized cost down, but also mitigates the risk, since larger projects involving multiple stakeholders and shared infrastructure reduce the likelihood that a failure in one part of the value chain compromises the entire system.

A key implication of this trend is that multiple transport methods may be employed to transfer CO_2 from various emission sources to centralized storage sites. While project-specific requirements will ultimately determine the optimal value chain, it is possible to foresee the development of large pipeline backbones or large carbon dioxide vessels for transporting CO_2 accumulated from several different emitters.

With many offshore reservoirs being potential CO_2 storage locations, offshore injection from ship or through an offshore unit may become an attractive solution because it avoids the need for a shore terminal and pipeline to the reservoir. We expect the smallest and more isolated emitters to transport the liquid CO_2 by truck, or train if a railway is already in place.

However, integrated transport and storage networks servicing multiple emitters do face significant challenges. Some challenges include flow assurance issues, the need to identify and meet strict CO_2 purity specifications (i.e. permitted impurity levels), interdependencies, and overall increased complexity.

Differences in terrain, levels of urbanization, and policies are influencing the different CO_2 transport and storage infrastructure in different regions. In the US, the availability of vast, non-urbanized, and often flat terrain, as well as cheaper onshore storage options, are resulting in a preference for dense phase CO_2 transport through large onshore pipelines and onshore storage. In Europe, onshore storage is less prevalent, and not allowed in some countries. High population density results in gas phase transport dominating onshore pipeline development due to safety concerns and stricter regulations, while we expect offshore pipelines to mostly operate in dense phase. Ship transport, especially in the North Sea or the Mediterranean Sea, will likely play a key role in transporting CO_2 between shore terminals or via offshore injection. In Asia, high-emitting countries such as Korea and Japan are considering long voyage ship transportation to countries like Malaysia, Indonesia, and Australia. In other parts of the world, depending on regional features, different countries are looking into all four transport methods, with pipelines being predominant for short to medium distances onshore and ships for longer distances offshore. The choice of the storage locations is usually determined by technical, policy, and economic constraints.

Generally, ships, trucks, and trains offer a more flexible transport solution than pipelines. For smaller transportation volumes, and in the initial stages of value chain development, these transportation modes can be a more viable solution. Ships, trucks, and trains are also an option where pipelines are not feasible due to terrain, local regulations, or similar constraints.

CO_2 utilization

Carbon dioxide utilization involves capturing CO_2 emissions and converting them into valuable products, like fuels, chemicals, and building materials. This approach not only helps reduce greenhouse gas emissions, but also promotes a circular economy by transforming waste into resources. By leveraging innovative technologies, CO_2 utilization can play a role in mitigating climate change. To understand the specific climate benefits of CO_2 utilization, a full life-cycle assessment should be performed.

230 $MtCO_2$
Estimated amount utilized in commercial applications annually

75 $MtCO_2$
30% used in EOR

130 $MtCO_2$
56% used in chemical industry

Source: IEA, 2019

Established industrial uses of CO_2 as a commodity

IEA reports that around 230 $MtCO_2$ are used in commercial applications annually, primarily in enhanced oil recovery and fertilizer production (IEA, 2019).

Enhanced oil recovery (EOR): EOR using CO_2 involves injecting carbon dioxide into oil reservoirs to increase the extraction of crude oil. CO_2 acts as a solvent, reducing the viscosity of the oil and allowing it to flow more easily to production wells (C2ES, 2019). Annual use is approximately 70 to 80 $MtCO_2$. The IEA commentary by McGlade (2019) discusses the potential for CO_2 EOR to result in net-zero or even carbon-negative oil production. Some sources suggest 37% reduction in CO_2 emissions per barrel compared to conventional oil production (CATF, 2019).

Chemical industry:
– **Fertilizer industry:** CO_2 is used as a feedstock that reacts with ammonia to form urea, a vital nitrogen-based fertilizer. Annual use is approximately 130 $MtCO_2$.
– The Solvay process is an industrial method for producing sodium carbonate (soda ash) used in glass manufacturing, pulp and paper processing, and other industrial processes.

Food and beverage industry: CO_2 is extensively used in the food and beverage industry for various applications.

– **Carbonation:** CO_2 is used to carbonate beverages such as beer, soft drinks, and sparkling water, giving them their characteristic fizz and preventing the growth of bacteria and fungi.
– **Preservation:** CO_2 helps preserve grains, fruits, and vegetables by preventing pest infestation and maintaining freshness through Modified Atmosphere Packaging (MAP) or Controlled Atmosphere Packaging (CAS).
– **Freezing and refrigeration:** CO_2 is used in cryogenic freezing and as a refrigerant to preserve the taste and texture of food items. Dry ice, a solid form of CO_2, is also used for shipping and transporting frozen foods.
– **Solvent:** CO_2 is used in various industrial processes due to its unique properties. In supercritical form, CO_2 acts as an effective solvent for extracting compounds such as in the decaffeination of coffee and the extraction of essential oils. Its non-toxic nature and ability to operate at relatively low temperatures make it ideal for preserving the integrity of sensitive materials.

Welding: CO_2 is commonly used in welding as a shielding gas, particularly in Gas Metal Arc Welding (GMAW) or Metal Inert Gas (MIG) welding.

Agriculture: CO_2 is used in greenhouses to enhance plant growth through a process known as CO_2 enrichment. Increasing CO_2 levels in a greenhouse can significantly boost photosynthesis, leading to faster and more robust plant growth.

Emerging CO_2 conversion applications

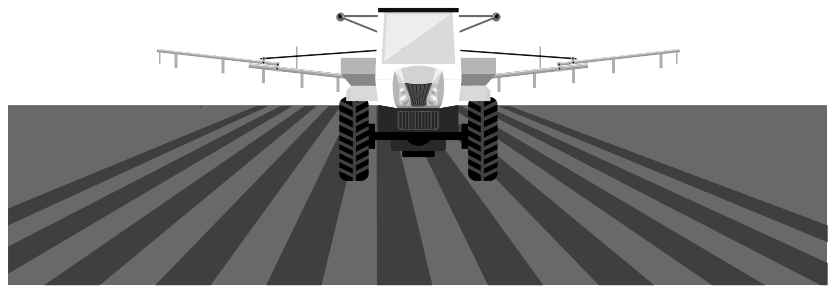
Emerging applications are gaining interest and projections suggest that by 2030, new pathways might capture an additional 15 $MtCO_2$ annually (IEA, 2019). Below are some of the leading applications among potential pathways of CO_2 conversion.

Fuels
– **Synthetic fuels:** CO_2 can be converted into synthetic fuels like methanol and ethanol, which can be used in transportation.
– **Sustainable aviation fuel:** CO_2-derived fuels are being developed for use in aviation, offering a greener alternative to traditional jet fuels.

Chemicals
– **Polymers and plastics:** CO_2 can be used as a feedstock to produce various polymers and plastics, reducing reliance on fossil fuels.

Building materials
– **Concrete:** CO_2 can be utilized in the production of concrete, where it is permanently stored, reducing the carbon footprint of construction.
– **Aggregates:** CO_2 can be converted into aggregates used in construction.

Recent technological developments in CO_2 conversion have significantly advanced the potential for transforming carbon dioxide into valuable products. Continued research and development is still required to overcome challenges and enhance CO_2 utilization technologies. The fertilizer industry and EOR still dominate CO_2 usage, while other applications collectively form a smaller but diverse segment of the market. While most captured CO_2 will need to be stored underground to meet climate goals, CO_2 utilization – though representing a smaller share – can play a role in stimulating demand and driving growth in carbon capture technologies. By creating value-added products, utilization pathways can help build the infrastructure and incentives needed for broader carbon management.



3 KEY CONSIDERATIONS

This chapter addresses two critical aspects of CCS deployment: the safety hazards of transporting and storing large quantities of CO_2, and the failure rates and performance of CCS projects. Effective management and robust safety standards and regulations are essential to mitigate risks and prevent environmental and health impacts. Additionally, we find that increased deployment and better performance of CCS projects is necessary, and understanding the challenges faced by past and current projects can guide better planning and execution.

Brevik CCS, Norway. Photo: Dag Jenssen / Heidelberg Materials AG.

3.1 SAFETY

Brevik CCS. Photo: Dag Jenssen / Heidelberg Materials AG.

As with many process industries, there are hazards associated with the large-scale handling of CO_2. This section describes the types of hazards that can occur throughout the CCS value chain and highlights challenges that stakeholders of CCS projects must be aware of to successfully manage these hazards.

Hazard to humans

With the advent of CCS, where pipeline systems are likely to carry liquid phase CO_2 in the order of 10s if not 100s of thousands of tonnes, the potential for widespread exposure to hazardous concentrations of CO_2 will exist.

CO_2 occurs at a concentration of 0.04% in the air and is a normal component of blood gases in humans. However, CO_2 can be hazardous if inhaled at high concentrations. There is a hazard of asphyxiation if CO_2 displaces oxygen in the air, and inhaling elevated concentrations of CO_2 can trigger adverse effects on the respiratory, cardiovascular, and central nervous systems. Depending on the CO_2 concentration inhaled and exposure duration, toxicological symptoms in humans can include headaches, increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma, and death (Wickham, 2003).

Breathing air with a CO_2 concentration of around 5% will cause headache, dizziness, increased blood pressure, and uncomfortable and difficult breathing (dyspnoea) within a few minutes. At CO_2 concentrations greater than 17%, loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death can occur within one minute of initial inhalation (Holt & Simms, 2022).

To effectively manage the risks associated with handling large quantities of CO_2, stakeholders of CCS projects need to have a full understanding of the impact CO_2 has on the human body. Further details on the impact of CO_2 on humans can be found in *CO2RISKMAN, Level 3* (DNV, 2021) or in the UK HSE's *Major Accident Hazard, human vulnerability guidance* (HSE, 2003).

Low temperature hazards

Releasing liquid or supercritical phase CO_2 to the atmosphere – whether through venting or a leak – will result in a phase change as the CO_2 depressurizes. Depending on the inventory temperature, the CO_2 will become vapour or form solid CO_2, widely known as 'dry ice'. Anyone exposed may suffer cryogenic burns and/or impact injuries.

Inhaling air containing solid CO_2 particles within a release cloud is particularly hazardous as this could also result in cryogenic burns to the respiratory tract and additional toxicological impact from CO_2 sublimation in the lungs. This risk of inhaling dry ice particles is only in the immediate vicinity of the release, especially inside any enclosures (e.g. compressor house, valve pit, etc.) where a release occurs. The cryogenic hazards are likely localized in near field of pipeline or facility releases with limited impact offsite.

Hazards for vehicles

Internal combustion engines (ICEs) require oxygen from the air to burn fuel. If the air being drawn into the engine has a significantly elevated concentration of CO_2, it could impair the engine performance and potentially cause it to stall or stop. In addition to damage to the vehicle, this presents a risk to personnel: if a vehicle stalls, the occupants could have increased exposure to the released CO_2 and limited means of escape. The exact CO_2 concentrations required to stall an engine depends on factors such as engine type, engine management unit, and load and fuel type.

While significant research on the potential impacts of CO_2 on ICEs is lacking, available data suggests that concentrations around 200,000 ppm (20%) may be the threshold where engine performance begins to degrade. Higher concentrations could impede evacuation or emergency response efforts by affecting vehicle operation in localized high-CO_2 areas. The ongoing Skylark Joint Industry Project (JIP) in the UK (DNV, 2024c) is expected to address this issue.

Hazard management

As CCS scales and spreads to new sectors and regions, risks must be carefully managed. This requires an adequate understanding of the properties and behaviours of CO_2 in the different parts of the CCS value chain and the application of proper hazard management processes. It is DNV's view that the major accident hazard risks from a CO_2 handling system within a CCS operation can be managed to well within acceptable limits if suitable knowledge and management processes are in place.

Hazard management challenges to be considered include:

- **Inadequate hazard appreciation:** whilst there are many aspects of CCS that are tried and tested, there are also aspects that are new. As CCS becomes a more mature industry, ongoing research and design and operation standards will help to ensure the effective understanding and management of hazards.
- **Integrity threats:** the CO_2 and impurities in the CO_2 stream have characteristics that can increase the likelihood of system leaks. These threats include:
  - Material incompatibility: liquid phase CO_2 is an excellent solvent that can break down some lubricants and CO_2 is highly invasive and capable of damaging some elastomers (e.g. seals).
  - Internal corrosion: CO_2 in combination with water and other components – such as SO_X and NO_X – may form acid drop-outs which are highly corrosive to carbon steels.
  - Low temperature and solid CO_2 formation: CO_2 depressurization (by design or by accident) can result in temperatures within systems and released plumes that could cause damage to equipment. In addition, significant quantities of solid CO_2 can form within systems or any release which could add to the low temperature issue and cause system blockages.
- **Mixture phase behaviour:** the phase diagram of pure CO_2 is well documented, but the presence of low levels of impurities within the CO_2 stream – such as hydrogen and nitrogen – can result in significant changes to the phase envelopes and the behaviour of the fluid.
- **Inhalation effects:** as discussed earlier, inhalation of large concentrations of CO_2 can have toxicological impacts and/or result in asphyxiation for both humans and nearby animals and livestock.
- **Hazard assessment:** assessing the risk from hazardous leak events involves frequency analysis, release modelling, and harm/consequence assessment. The practice of risk assessment is extensive, but there are aspects of assessing CO_2 stream leaks that need appropriate consideration:
  - Propagating pipeline cracks: the considerable knowledge and experience with managing the risks associated with propagating cracks in natural gas and other pipelines is now being used for CO_2 pipeline design.
  - Dispersion of CO_2 plumes: the behaviour of CO_2 plumes, whether through accidental releases or planned venting, is highly dependent on the phase being released, the velocity of the release, and the topography of the terrain. Additionally, CO_2 is a heavy gas and therefore does not disperse readily in the atmosphere and will collect in low-lying areas. Consequence modelling software is being developed to manage these challenges.
  - Invisible CO_2 cloud: CO_2 concentration within a release cannot be assessed by looking at the size of the visible cloud. CO_2 vapour is invisible. The visible cloud that is commonly seen when liquid CO_2 is released is water vapour in the surrounding air condensing due to the cold temperature of the CO_2 stream. Fog from a cold CO_2 release could potentially impair visibility and emergency response. In contrast, a leak from a hot CO_2 inventory would probably not form any visible cloud.

As CCS scales and spreads to new sectors and regions, risks must be carefully managed.

Establishing the Porthos CO_2 transport route under the Dintelhaven shipping port in Rotterdam, Netherlands. ©PorthosCO2.

Safety standards
Different regions have varying regulatory regimes and CO_2 safety standards. Europe and North America have the most comprehensive. The regulatory regimes governing CO_2 pipeline infrastructure in Europe and North America are summarized by the International Energy Agency *Greenhouse Gas R&D Programme* (IEAGHG) on behalf of the Global CCS Institute (IEAGHG, 2013).

There are many other examples of regulations and standards covering all parts of the CCS value chain, from capture to transport (e.g. pipelines or shipping) and storage.

Some examples of standards include:
In the US, *CFR 49 Part 195* applies, which was amended in 1989 to include CO_2 in the former 'Hazardous Liquid' category. Before this, CO_2 pipelines had to meet codes for natural gas pipelines. The *Pipeline Safety Authorization Act* of 1988 granted the Pipeline and Hazardous Materials Safety Administration (PHMSA) the authority to regulate the transportation pipelines carrying CO_2. PHMSA is an agency of the US Department of Transportation responsible for overseeing and regulating the transportation of hazardous materials, including CO_2 pipelines.

Canada has its own regulation for CO_2 pipelines, *CSA standard Z662*.

In Europe, *Directive 2099/31/EC on geological CO_2 storage* states that the framework used for natural gas pipelines is adequate to regulate CO_2 as well.

The following ISO standards apply to carbon capture activities:

– ***ISO 27919-1:*** *Carbon dioxide capture – performance evaluation methods for post-combustion CO_2 capture integrated with a power plant*

– ***ISO 27913:*** *Carbon dioxide capture, transportation and geological storage – pipeline transportation system*

– ***ISO 27914:*** *Carbon dioxide capture, transportation and geological storage – geological storage*

CO_2 specification

A specification that defines the maximum levels of various impurities in CO_2 is a necessary part of ensuring safe and cost-efficient CCS value chains. Impurities in CO_2 can impose risks to the integrity, operability, and the injectivity of CO_2 along the value chain. The composition and level of impurities can vary considerably depending on the source (the capture process and the feed stream composition from which the CO_2 was captured). Composition can have significant implications for critical design and operational parameters. Similarly, impurities can affect the phase behaviour of CO_2, the physical properties which influence transport dynamics, and the water solubility which can lead to hydrate formation. It is also crucial to maintain strict control over water content composition and to understand the cross-effects of impurities, which currently is an area of ongoing research. Importantly, the development of shared transport and storage infrastructure introduces CO_2 with different impurities from multiple emitters, impurities which can react chemically and form acidic species and corrosive compounds.

The reaction mechanisms and kinetics (time scale) can exacerbate corrosion rates and challenge the integrity of the infrastructure. Unfortunately, these mechanisms and kinetics are not always well understood, which can make developing a specification difficult.

A CO_2 specification impacts infrastructure design, material selection, and operation. It is thus a necessary design basis. An appropriate specification requires a full CCS value chain perspective considering each capture site and the infrastructure for transport and storage. Detailed analysis must be performed for each value chain. This must identify and assess risks and define appropriate requirements and measures for ensuring that CO_2 can be transported and stored safely, effectively, and without causing any damage to the environment or system itself. Part of creating a specification is a cost trade-off analysis to consider the cost of removing impurities – either at the emitter site or at centralized processing steps along the value chain – compared to the cost of designing a system infrastructure that tolerates higher levels of impurities.

DNV has several ongoing Joint Industry Projects (JIPs) that address the impact of different compositions on risk of corrosion, material integrity, and the need to ensure accuracy and traceability in monitoring of quality of CO_2. These include SafeandSour, CO_2SafePipe, and CO_2Met QM. The industry has developed guidelines to support setting a CO_2 specification for value chains (Drageset et al., 2025; AMPP, 2023; Wood, 2024).

Impurities in CO_2 can impose risks to the integrity, operability, and the injectivity of CO_2 along the value chain.

3.2 HISTORICAL DEPLOYMENT AND PERFORMANCE OF CCS

Historically, CCS project failure rates have been high. Additionally, operational projects have performed at less than their nameplate capacity, on average. In some cases this is by design, and in others this is due to technical and/or economic issues.

Our projections (presented in Chapter 5) indicate CCS deployment is not growing in line with most IPCC-assessed scenarios consistent with 1.5 to 2°C. Indeed, we forecast that deployment by mid-century will be less than one-sixth of that required under DNV's own *Pathway to Net Zero* scenario (DNV, 2023b). Accelerated deployment is clearly needed, and reducing the number of project failures and improving the performance of operational facilities is fundamental. Lessons from prior failed and operational projects are well documented and critical to consider as new CCS projects, policy, and regulations emerge globally.

Historical deployment of carbon capture facilities
A recent analysis of carbon capture project announcements, realizations, and cancellations by Kazlou et al. (2024), found that carbon capture projects suffered from high failure rates of around 88% from 1972 to 2022. Failure rates are higher in more recent years due to sectors with higher failure rates comprising a larger share of the total planned project pipeline. The research also shows, via analogue industries, that much stronger government support could reduce failure rates down to almost 45% (Kazlou et al., 2024).

Historically, gas processing has dominated the CCS sector, comprising around 85% of installed capacity globally. Gas processing is a mature industry with more than 60 years of experience, a firm business case to achieve market specifications for gas, and is closely tied to gas and oil prices as most of the CO_2 is used for enhanced oil recovery. Gas processing projects have similar failure rates to other mature industries at around 40%.

In the past 25 years, other sectors have also deployed CCS – predominantly in power and industrial processes. With emissions reductions a much less firm business case, and the technology still adapting to the very different conditions, the performance of these projects is far more variable. These projects have much higher historical failure rates in excess of 70% and require strong policy and financial support to succeed.

Reducing the number of project failures and improving operational performance is critical for accelerating CCS.

One of the key reasons for project failure is a lack or removal of policy and/or financial support. For a CCS project to proceed, there must be a means to cover the associated costs. This is typically provided through policy support. In the period 2010 to 2015, as governments adjusted their priorities following the global financial crisis, policy support for CCS projects often failed to materialize or was removed. For example, the removal of UK Government financial support impacted investor sentiment and ultimately led to the cancellation of the White Rose project in 2015 (Energy and Climate Change Committee, 2016).

Cross-chain risk is another key issue as the different parts of a CCS value chain are often developed by different, but interdependent, parties. Many early CCS projects failed due to issues with a specific part of the value chain. For example, the cancellation of the Kemper project in 2017 which planned to capture CO_2 from coal gasification. The availability of cheap natural gas made the coal gasification process itself economically unattractive. This was compounded by both budget and construction issues (Kelly, 2018).

In some cases, stakeholder concerns from governments or the public have contributed to project failure. In 2010, the Barendrecht CCS project in the Netherlands was cancelled due to a combination of a change in consensus on the need for the project at the government level and local opposition (Egmond and Hekkert, 2015). To avoid similar cancellations, CCS project developers must transparently engage with and consider the concerns of stakeholders (Section 4.2).

Historical performance of operational carbon capture facilities

No two operational carbon capture projects are the same; project performance is highly project specific. To investigate historical performance, DNV has developed a comprehensive database of annual and monthly carbon captured, as reported by operators, for over 30 operational projects globally (Figure 3.2). This represents over 90% of global carbon capture capacity and covers the period from 1986 to 2023. The utilization rate appears relatively variable in the 1980s and 1990s due to the outsized influence of one major project on the data. From the mid-1990s onwards utilization has remained relatively stable around 40 to 60%.

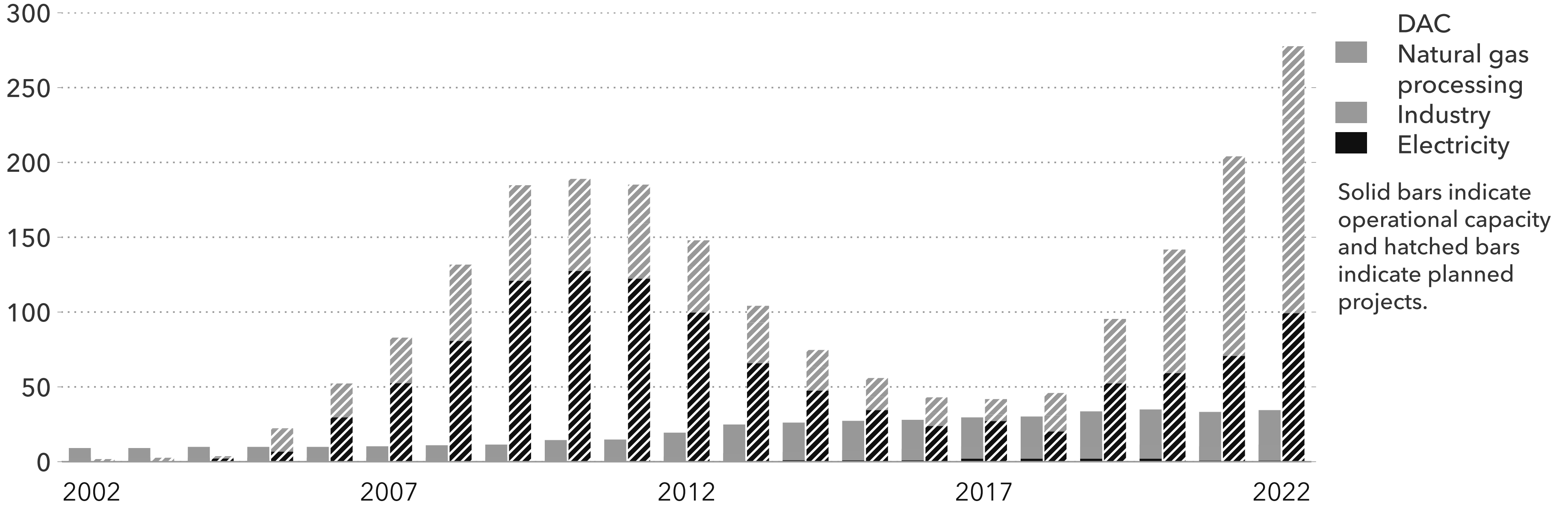
We found that the communication around carbon captured, capacity, and capture rates can be unclear, and the three terms are often used interchangeably. The deep-dive into each project has addressed these issues to give accurate capacities.

Between 1986 and 2023, the average utilization rate (amount of CO_2 reported captured vs the reported capture capacity of a project) is 53%, and increases to around 60% in the most recent five years of data.

FIGURE 3.1

Operational capacity and planned capacity additions

Units: $MtCO_2/yr$

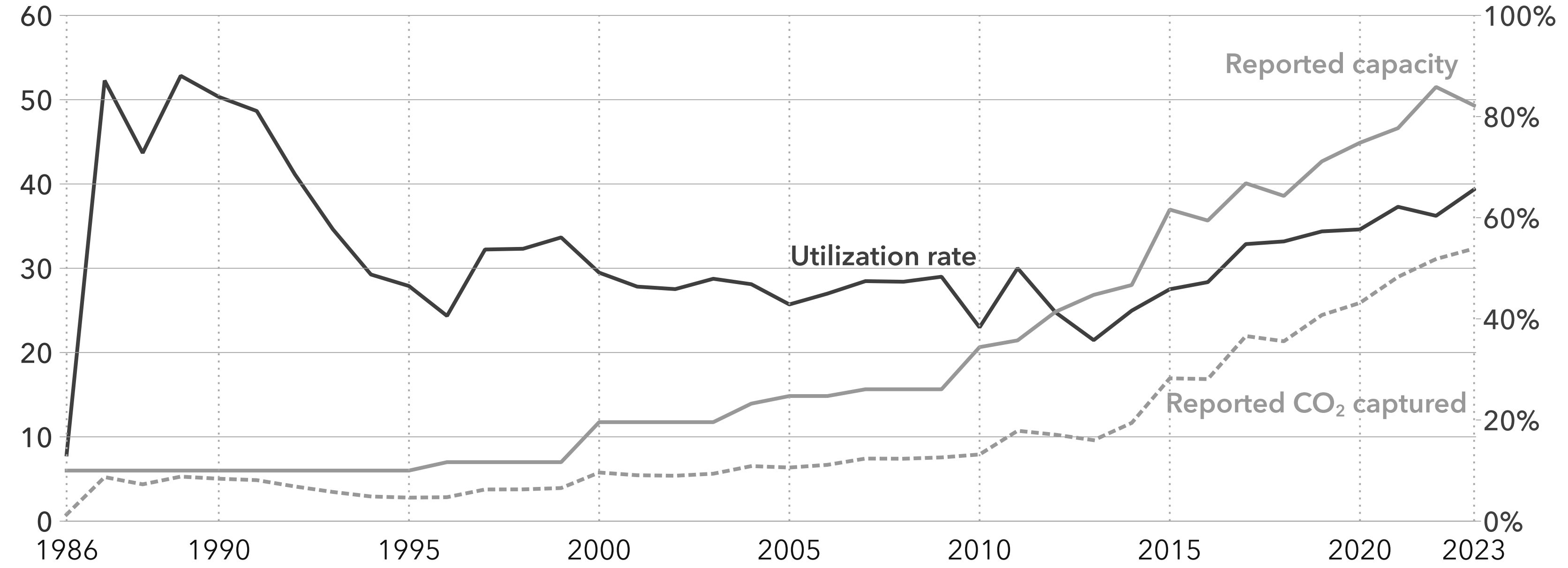


Note: Reproduced from Kazlou et al (2024) with permission from the authors.

FIGURE 3.2

Reported capacity, reported CO_2 captured, and utilization rates of operational carbon capture projects where available

Units: $MtCO_2/yr$ (left axis), Percentages (right axis)



Note: 30 operational carbon capture projects globally. Data source: DNV (2025)

Excluding gas processing projects (as they have different economics and incentives), the utilization rate drops to 46% between 2000 and 2023, with a value around 50% in the most recent five years of data. The total amount of CO_2 captured in 2023 was around 33 Mt, with the majority of this used for enhanced oil recovery (Section 2.3) or vented. Of the total capacity, around 85% captures CO_2 for EOR.

The reasons behind the performance numbers are unique to each project, however one general observation is that gas processing projects connected to large gas fields tend to have higher utilization rates with less variability. This is due to the constant production of gas, high CO_2 concentrations in the feed gas, and a need to remove CO_2 to meet technical product specifications that is decoupled from a need to store CO_2. In smaller gas processing plants, such as Sleipner in Norway, the utilization factor is tied directly to the production curve of the gas field. Here the capacity is the maximum expected at the peak of gas production.

For projects outside of the gas processing sector, the utilization rates are much more variable. In some cases, projects have had issues with equipment that result in unexpected downtime or maintenance, lower than expected capture rates, or higher than expected amine degradation rates. Others are tied to the demand for what they produce, be that syngas, hydrogen, or power. In the case of the Century gas processing plant, the development of the shale gas industry in the US caused prices to collapse below the breakeven point for the Pinon field when including the necessary gas processing costs and CO_2 sales, resulting in the mothballing of one capture unit and low utilization of another (White et al., 2023).

A consistent approach to reporting operational performance and transparency regarding the data could offer significant benefits to the CCS industry. Such data could enable more accurate quantification of CO_2 avoided and provide the basis for benchmarking and performance improvements.

Phrase	Description	Common units
Capture capacity	The total amount of CO_2 that the capture equipment is designed for. This is usually given in units of mass per unit time.	Million tonnes per annum (MTPA or $MtCO_2$/yr), thousand cubic feet per day (MCF/d), or tonnes per hour (t/h).
CO_2 captured	The mass or volume of CO_2 that the equipment removes from the gas mixture that enters it. This can sometimes be higher over a certain period than the capture capacity as the capture capacity is normally based on an average volume with a particular concentration of CO_2 entering the equipment. Running more gas mixture through the equipment results in more capture in some cases.	MCF, m^3, kg, or tonnes
Capture rates	Measure of the proportion of CO_2 that is removed from the gas mixture that enters the capture equipment.	%, e.g. 85% capture rate
CO_2 avoided	The amount of CO_2 that would have been emitted if the plant did not have capture equipment fitted, minus the amount of CO_2 captured, and with any emissions from the capture equipment, venting, upstream (sourcing and utilities), and downstream (transport and injection) added. It is always smaller than the amount of CO_2 captured and can even be negative in some cases with high upstream emissions and low capture rates.	Tonnes, kg

Brevik CCS. Photo: Dag Jenssen / Heidelberg Materials AG.

4 POLICY AND FINANCING

Strong policy support including incentives, mandates for emissions reductions, and carbon pricing mechanisms are essential to scale CCS deployment. Clear regulations will also be essential to overcome barriers to deployment. This chapter explores the policies and financing mechanisms most likely to support CCS deployment, how projects can gain public acceptance, and the complex regulatory and legal requirements. We also discuss the cost of capital for CCS projects and deep dive into how carbon markets are driving carbon removal technologies. We finish with a summary of the current status of CCS by region.

4.1 THE POLICY CONTEXT FRAMING CCS INDUSTRY DEVELOPMENTS

This section discusses the policy landscape globally and across the ETO regions. CCS deployment is largely policy driven, intrinsically linked to the urgency of mitigating emissions and climate risks. If government attention fades, so do CCS investments. Governments play a key role in steering emissions reduction plans and supporting research and development, deployment, and scaling. However, carbon pricing and sector mandates appear essential for integrating CCS into emission-intensive industries as part of a 'new normal' and making a meaningful contribution towards decarbonizing the energy system.

CCS projects are advancing where there is policy and regulatory certainty. Numerous policies have emerged that aim to reduce risks in first-of-a-kind projects, clusters, and common infrastructure. Both the public and private sectors must invest significantly. Those involved in CCS value chains, along with their respective responsibilities, must be coordinated through regulatory frameworks (see discussion in Section 4.5) that unify standards and safety requirements and ensure effective storage.

We observe five main drivers framing CCS policy developments.

1 CCS recognized as a necessity for net-zero emissions

To achieve the *Paris Agreement* goals of limiting global warming to well below 2°C and pursuing efforts to limit the temperature increase to 1.5°C, CCS and direct air capture (DAC) are essential technologies (IPCC, 2023). The first Global Stocktake outcome from COP28 – informing the nationally determined contributions due in 2025 – calls for accelerated use of carbon capture, utilization, and storage (paragraph 28(e)) alongside energy efficiency and renewable energy (UNFCCC, 2024).

CCS and renewables are most often not competing alternatives; both are needed to reduce anthropogenic GHG emissions. DNV highlights CCS's critical role in:

A. Industrial process emissions not related to energy or fuel combustion.

B. Hard-to-decarbonize sectors that lack direct electrification options.

C. Removing atmospheric CO_2 to counterbalance residual emissions and ultimately reach net-negative emissions.

Additionally, the lifetime of existing power sector assets, low-carbon dispatchable power needs, and interest in using domestically available fossil resources mean CCS will likely play a role in the power sector.

2 Frontrunner high-income countries leading support

Early actions by wealthy countries that are responsible for most emissions are at the forefront of advancing CCS technology and reducing costs through learning effects and economies of scale. These actions are necessary to prepare the ground for CCS adoption globally, leveraging the capacity established by high-income countries (competence/finance availability) and aligning with the UNFCCC's principle of common but differentiated responsibilities in addressing climate change.

The Carbon Management Challenge (CMC), launched by the Major Economies Forum on Energy and Climate Change in 2023, galvanized such an approach to early action. Participant countries, which account for roughly 80% of global GDP and GHG emissions (White House, 2023), set a collective CCS or carbon dioxide removal (CDR) goal to advance carbon management projects to one gigatonne annually by 2030. We find that this goal will fall significantly short (see Chapter 5). Nevertheless, the challenge has succeeded in expanding policies and funding programmes (see The CCS Policy Toolbox at Work in ETO Regions on Page 35) to support projects in diverse sectors with varying technology readiness levels (see Section 2.1) and advancing CCS value chain developments.

Some countries have set explicit million tonnes per annum (MTPA) capacity targets, but only a few have stated their ambitions towards 2040 and

2050. These targets establish pro-CCS signals and planning horizons. However, durable support and incentivization from policy frameworks will be needed to ensure sufficient investment, market certainty, and momentum for long-term infrastructure planning and project lifecycles.

3 Overcoming cross-chain risk

Infrastructure and storage must develop alongside capture projects to overcome cross-chain risks; that is, risks faced by each part of the value chain should another part fail to operate for any reason (Lockwood, 2024). Emitters need transport and storage options to invest in capture, while infrastructure investors require certainty on future demand and CO_2 volumes. Investment decisions need reasonable certainty across the CCS value chain. This necessitates quick policy iterations to ensure co-evolution of capture and common infrastructure.

Governments play a key role in mitigating cross-chain risks. In regions with state-owned enterprises (SOEs) leading full-chain development, this challenge is reduced. However, in regions with distinct entities and private investors in the CCS value chain, these risks are typically mitigated through contractual arrangements and policy.

Examples from Europe illustrate government efforts to derisk infrastructure investments:

- The EU Joint Research Centre estimates that over USD 13.5bn is needed by 2030 for investments in CO_2 transport networks (Tumara et al., 2024). The list of supported Projects of Common Interest (PCI) eligible for funding from the Connecting Europe Facility (November 2023) included 14 CO_2 network projects that also benefit from fast-tracked permitting (EC, 2023a). A new call for PCI proposals was launched on 3 April 2025.
- At the member state level, Denmark provides USD 41m in funding to the Greensand and Bifrost projects. Norway subsidizes 80% of the Longship project, including Northern Lights, which signed the first cross-border CO_2 transport agreement with Yara's Sluiskil project in the Netherlands (Yara, 2023). The UK supports the Northern Endurance Partnership (NEP, 2024) and has adopted a regulated model to ensure cost recovery through regulated tariffs paid by users (Lockwood, 2024).

4 Balancing 'carrot and stick' approaches to sustain economic viability

To make CCS projects economically viable, either a disincentive ('stick') to emit and/or an incentive ('carrot') to capture CO_2 must be sufficiently high.

CO_2 has been captured and used for enhanced oil recovery (EOR) in oil and gas operations since the 1970s. In other sectors, such as power and industry, CCS is a cost. 'Emitting' will always be the cheaper option unless a sufficient value/price is put on carbon. Only recently, demand for carbon capture grew in Europe and the US due to the EU *Emissions Trading System* (ETS) (the largest stick) and the 45Q tax credit in the US *Inflation Reduction Act* (the largest carrot). This proves these methods are highly effective in accelerating CCS projects globally and highlights the importance of placing a value or price on carbon to incentivize emissions reduction.

Projects will only emerge through market dynamics if the cost of emitting or reward for storing is greater than the cost of CCS. Experience from Europe, Canada, and increasingly China, shows economy-wide carbon pricing as a central decarbonization instrument. Europe is also raising revenue through the ETS for clean technology spending via the EU Innovation Fund. Such revenue can be earmarked and funnelled back to the industry sectors for CCS deployment purposes. Public acceptance can also be improved through recycling mechanisms, i.e. redistributing revenue generated from carbon pricing back to the public to help address the financial effects carbon pricing might have on households, such as energy prices.

Projects will only emerge through market dynamics if the cost of emitting or reward for storing is greater than the cost of CCS.

5 Fostering public trust and acceptance

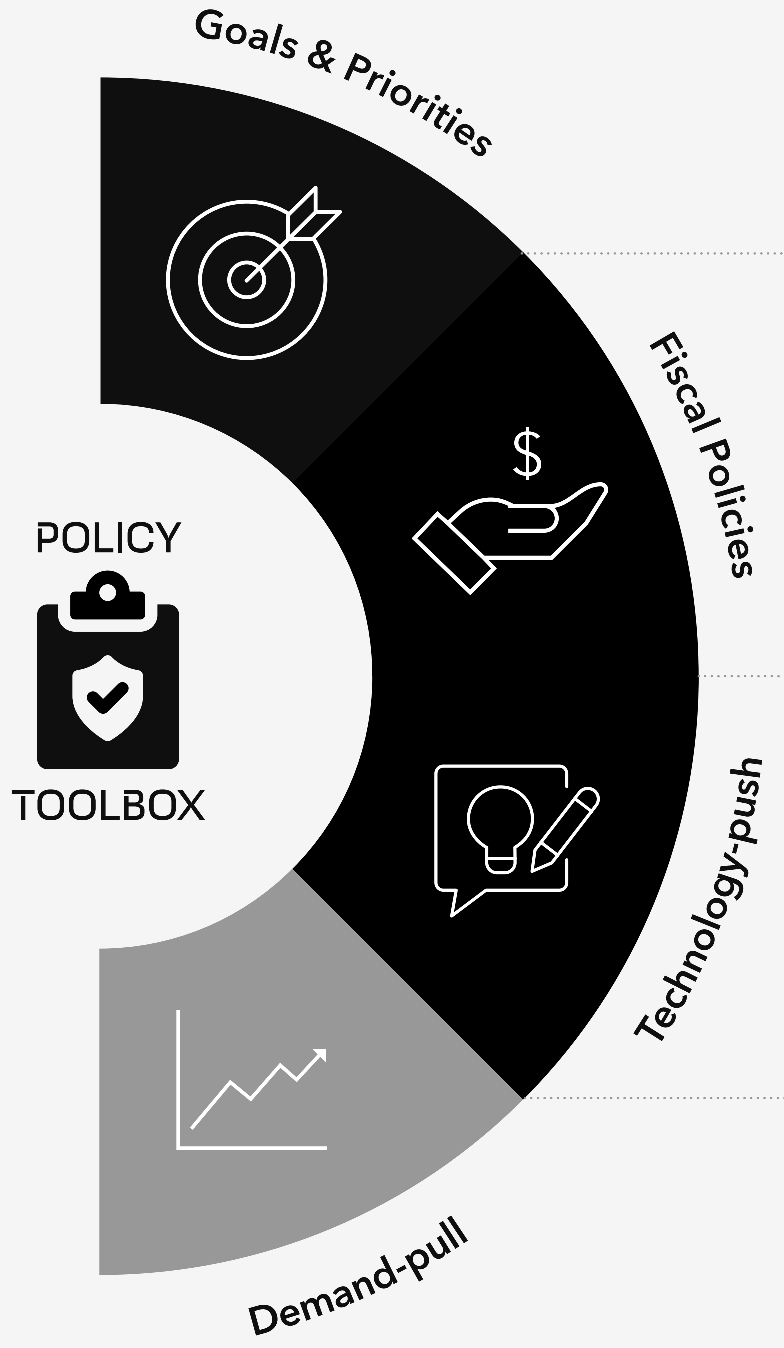
Public concerns about CCS projects include pipeline and storage safety, property value impacts, and broader environmental views on CCS as a viable solution. These issues, detailed in Section 4.2, affect project permitting and value chain setup. Building public trust and demonstrating societal and community benefits (jobs, revenue, climate stewardship) is crucial and requires engagement strategies from developers and regulators.

THE CCS POLICY TOOLBOX

CCS supportive policies and incentives include planning, fiscal instruments, technology-push, and demand-pull measures (see the figure to the right). Similar measures are highlighted by the IEA (IEA, 2023, page 35) though categorized differently.

While it is paramount to put a value and price on carbon, current carbon pricing schemes are too volatile and low to drive CCS forward on their own. A policy mix of complementary measures is essential in the early stages of industry development to move projects to implementation.

A policy mix is essential in the early stages of industry development to move projects to implementation.



Purpose: Structure and inform national and sectoral policy
- Carbon management plans for sector investment pipelines (e.g. MTPA capture targets)
- Legal/regulatory frameworks for CCS value chains (e.g. storage regulation, liability)
- Public-private partnerships for joint innovation undertakings (e.g. IEAGHG, Mission Innovation's CDR mission, Longship project)

Purpose: Integrate goals and level the playing field
- Public budgets and spending for alignment of financial flows with climate goals and low-carbon development
- Fiscal instruments for emissions reduction (e.g. tax credit incentives, carbon tax, emissions trading systems, energy tax differentiation on carbon content, and carbon border adjustment tariffs)

Purpose: Stimulate technology development and cost reduction
- Funding for feasibility studies, RD&D, and CAPEX contribution through grants, loans, and investment tax credits for projects
- Technical requirements for emission limits and emission intensity reductions
- Taxonomy classifying climate compatible economic activities (e.g. compliant sustainability investments)

Purpose: Stimulate demand and incentivize market uptake
- Mandates for emissions reduction (e.g. use of low-carbon energy, CCS and storage deployment, public procurement of low-emission goods like cement and steel)
- Funding for investments, capital expenditure (e.g. equipment, conversions)
- Economic instruments for OPEX mechanisms guaranteeing revenue streams (e.g. carbon contracts for difference)

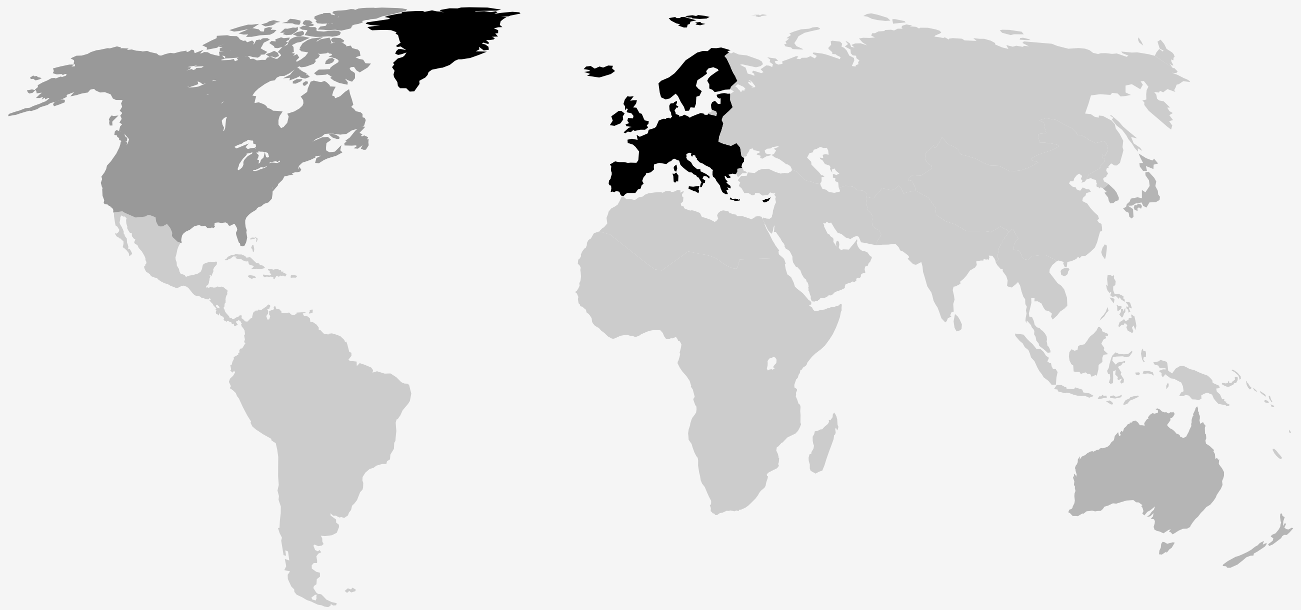
THE CCS POLICY TOOLBOX AT WORK IN ETO REGIONS

In the following pages we will give high-level examples of the policy toolbox at work in the ETO regions.

The US administration's CCS goals are unclear, but the 45Q tax credit will likely remain.

High-income regions

Europe (EUR)
North America (NAM)
OECD Pacific (OPA)



Goals & Priorities

- Most countries aim for net-zero emissions by mid-century. North America's leadership in CCS developments faces uncertainty due to energy/climate policy shifts and the US's withdrawal from the *Paris Agreement*.

- **EUR:** The EU policy framework has evolved from the *CCS Directive* (2009) to proposing the *Carbon Removals and Carbon Farming Regulation* (2024) for high-quality removals and the revised *Gas Directive* (2024) for low-carbon hydrogen. *The Industrial Carbon Management Strategy* (EC, 2024a) aims for storage capacity of 50 $MtCO_2$/yr by 2030 and 450 $MtCO_2$/yr by 2050, with milestones for regulatory improvements. Still, the Commission's assessment of member states' National Energy and Climate Plans estimated around 34 and 39 $MtCO_2$/yr capture and injection capacity, respectively, by 2030 (EC, 2023b). However, Austria and Germany have since released their carbon management strategies, pushing ambition levels upwards.

- **NAM**: The US administration's CCS goals are unclear, but the 45Q tax credit, part of the federal tax code since 2008 and enhanced by the IRA in 2022, will likely remain. It is believed that CCS policies included in the IRA could enable 200 to 250 $MtCO_2$/yr by 2030 (GCCSI, 2024a), while the US Department of Energy estimates 400 to 1,800 $MtCO_2$/yr by 2050 is needed to meet energy transition goals (DOE, 2023). Canada's *2030 Emissions Reduction Plan* (Government of Canada, 2022) focuses on CCS and removal in energy and industry. *The Carbon Management Strategy* targets around 16 $MtCO_2$/yr by 2030 (Government of Canada, 2023).

- **OPA:** Japan's *Act on Carbon Dioxide Storage Business* (May 2024) introduces a licensing system for CCS activities, targeting 13 $MtCO_2$/yr by 2030 and 240 $MtCO_2$/yr by 2050. South Korea increased its 2030 CCUS target from around 10 to 11 $MtCO_2$/yr (Korea Times, 2023) and passed the *CCS Act* (February 2024) covering licensing, storage regulations, and industry support. Standards for low-emission ships, including onboard CCS, are being revised (February 2025). Australia is modernizing its *Offshore Regulatory Framework* to facilitate more CO_2 import and storage. New Zealand plans to introduce legislation and a CCUS framework in 2025.

Fiscal

- **EUR:** Mature carbon pricing (CP) instruments are in place with emissions trading systems (ETS-1 and ETS-2 for buildings and road transport, which will be established in 2027) complemented by national taxation to incentivize emissions reduction. We project the regional average carbon price level applied to ETS-1 sectors to reach USD 150/tCO_2 by 2030, USD 220/tCO_2 by 2040, and USD 250/tCO_2 by 2050, and ETS-2 at around USD 50/tCO_2 in

2030 and USD 220/tCO_2 in 2050. Both aviation and maritime sectors are transitioning to full compliance under the EU ETS-1, with aviation reaching full payment by 2026 and maritime transport (large ships over 5,000 gross tonnage) by 2027.

- **NAM:** A minority of US states have CP policy in place. Canada has CP economy-wide with an announced trajectory to 2030. We project the regional average carbon price level to reach USD 20/tCO_2 by 2030, USD 30/tCO_2 by 2040, and USD 50/tCO_2 by 2050. The effective CP on industrial emissions is about 50% lower.
- **OPA:** Countries have mature CP instruments or are implementing them. We project the regional average carbon price level to reach USD 35/tCO_2 by 2030, USD 85/tCO_2 by 2040, and USD 130/tCO_2 by 2050.

Technology-push

- **EUR:** The EU's *Net Zero Industry Act* (EU, 2024) states that CCS technologies will be essential for achieving net-zero goals. The EU supports CCS projects through the Innovation Fund (funds raised by the EU ETS-1), providing USD 43bn from 2020 to 2030 (ENTEC, 2023) with up to 60% project funding for regular grants and up to 100% for competitive bidding. Additionally, the Connecting Europe Facility (CEF) offers co-funding rates of 50 to 75%, with the latter applicable to PCIs such as cross-border infrastructure (EU, 2021). National programmes complement EU funding, such as Sweden's USD 3.4bn *BECCS scheme*, the *Dutch SDE++ Programme* with USD 13bn, Denmark's USD 4.2bn CCS Fund (ENS, 2024), and the UK's USD 28bn investment in CCS and hydrogen clusters (Government of UK, 2024). Some countries also invest in DAC technology, including the UK's USD 133m and Switzerland's USD 20m to removal initiatives.
- **NAM:** The US administration's funding freeze puts the *Clean Energy Financing Program* at risk, including the USD 300bn loan guarantees for up to 80% of project costs. Uncertainty overshadows past CCS support such as USD 5.3bn for research (2011-2023), the 2009 *American Recovery and Reinvestment Act* funding the Petra Nova facility (CBO, 2023), and the USD 12bn from the *Infrastructure Investment and Jobs Act* (IIJA), also known as the 'Bipartisan Infrastructure Law'. We expect the IRA's 45Q tax credit – which distinguishes between capture-storge, capture-utilization, and capture via DAC – to continue. The 45V hydrogen tax credit regulations, which were finalized in January 2025 (IRS, 2025), are also related to CCS, though their removal is anticipated. Canada's *Carbon Management Strategy* (2023) is backed by USD 14bn federal funding over five years, including the *Energy Innovation Programme, Canada Growth Fund* (CGF) and CCS investment tax credit (ITC). The ITC covers 60% of DAC projects, 50% of capture projects, and 37.5% of transport and storage costs (2022-2030), with rates halving from 2031 to 2040. The CGF announced USD 1.4bn for a strategic partnership with Strathcona and proposed support for the USD 11.5bn Pathways Alliance project. Provincial incentives, like Alberta's *TIER* regulation, are also available.
- **OPA:** There are large funding programmes for decarbonization with a focus on CCS projects in industry, energy, and power sectors. Japan's *GX Promotion Strategy* supports CCS development with funding channelled from the Ministry of Trade, Economy and Industry and state-owned Japan Organization for Metals and Energy Security (JOGMEC), with the latter providing subsidies and support through equity investments and debt guarantees. JOGMEC selected nine priority projects (20 MtCO_2/yr), five for domestic and four for overseas storage, for commissioning by 2030 (JOGMEC, 2024). South Korea is channelling around USD 320bn (452trn won) in support/policy loans for climate initiatives through to 2030 (Shin, 2024). The government and banking industry will jointly invest an additional USD 6bn in climate technologies, including carbon capture. Tax reductions/subsidies are available to cover the construction and conversion costs of maritime vessels (Kosmajac, 2025). Australia's *Safeguard Transformation Stream* offers grants covering up to 50% of eligible expenses, with USD 380m allocated from 2023 to 2027 to support decarbonization investments in trade-exposed facilities. The *Carbon Capture Technologies Program* supports novel CCU technologies and hard-to-decarbonize sectors (Government of Australia, 2023).

Demand-pull

- At COP28, Canada, Germany, the UK, and part of the Industrial Deep Decarbonization Initiative, promoted the *Green Public Procurement Pledge* to boost market demand for decarbonized cement, concrete, and steel.
- **EUR:** We expect broader adoption of OPEX payments through carbon contracts for difference (CCfD) beyond country pioneers like the Netherlands and the UK following *Draghi* report recommendations (EC, 2024b). CCfD set a strike price and provide a hedging component against volatile EU ETS prices thereby guaranteeing financial benefit to compensate for the cost of CCS. For example, Germany's USD 5.6bn bilateral carbon contract scheme will award 15-year contracts through competitive bidding to help decarbonize industry. The *Net-Zero Industry Act* mandates oil and gas producers to provide storage capacity proportional to their shares of EU oil and gas

production in the period 2020 to 2023 to help establish full CCS value chains. In late May, 2025, the EU Commission announced the 2030 contribution obligations on 44 entitities.

- **NAM:** The 45Q tax credit incentivizes companies to use CCS for up to 12 years. The *IRA* allocated USD 6bn for the demonstration and deployment of low-carbon industrial production technologies through grants, loans, and guarantees (2022 to 2026). Canada's USD 5.9bn *Strategic Innovation Fund – Net Zero Accelerator* aids large industrial emitters in adopting clean technology. Additionally, Canada committed USD 7bn to CCfD and proposed draft regulations to cap and reduce emissions from upstream oil and gas facilities by 35% below 2019 levels by 2030 (Government of Canada, 2024).

- **OPA:** South Korea plans to introduce CCfD and provides soft loans for large-scale carbon-neutral technology projects. Japan will support capital expenditures in iron and steel, chemicals, paper, and cement with around USD 8.5bn over 10 years (GR Japan, 2024b). New Zealand's GIDI Fund will cover up to 50% of project costs for industrial decarbonization. Australia's *Safeguard Mechanism* requires large emitters to reduce emissions by 4.9% annually from 2023 to 2030, generating Safeguard Mechanism credit for improvements below the baseline which can be sold for additional revenue.

Middle-income regions

Goals & Priorities

- **CHN:** China aims to reach peak carbon emissions by 2030 and carbon neutrality by 2060. The '1+N' policy framework guides sector-level CCS policies (DNV, 2024d; GCCSI et al., 2023). The updated dual control system (Government of China, 2024) for the *15th Five-Year Plan* (2026-2030) focuses on carbon intensity and total volume control. This plan recognizes CCS for fossil energy decarbonization. The *NDC* and *Long-Term Low GHG Emission Development Strategy* support large-scale CCS demonstration and industrial application. The updated carbon capture road map (late 2024) includes energy and industrial sectors and emphasizes DAC technology development (China Daily, 2024).

- **MEA:** Countries in the Gulf Cooperation Council have set goals to achieve net zero by 2050 or 2060. The United Arab Emirates (UAE) targets 10 $MtCO_2$/yr capture capacity by 2030, the Kingdom of Saudi Arabia (KSA) targets 44 $MtCO_2$/yr, and Qatar aims for 11 $MtCO_2$/yr by 2035. Turkey's *Long-Term Climate Strategy* (2024) aims for net zero by 2053, focusing on CCS for cement, iron, and steel. Algeria and Egypt are developing regulatory frameworks, with Egypt signing a memorandum of understanding with Greece for cooperation on utilization and to identify storage projects (Herema, 2025).

- **LAM:** Countries have 2050 and 2060 net-zero targets. Brazil leads the region with its *Fuels of the Future* law (CDR, 2024), that regulates capture, transport, and storage. The National Agency of Petroleum, Gas, and Biofuels (ANP) is to oversee CCS activities and permits for geological storage.

- **SEA:** Singapore aims for net zero by 2050 and is progressing at pace with CCS strategy targets to capture 2 $MtCO_2$/yr by 2030 and over 6 $MtCO_2$/yr by 2050. Singapore is evaluating cross-boarder CO_2 transport with storage options being examined in Australia, Indonesia, and Malaysia. Indonesia and Malaysia aim to be storage hubs for the region's emissions. They are at an advanced stage of developing regulation. Emissions from industry in Japan and South Korea will drive this. For example, Malaysia signed a CO_2 storage agreement with Japan. Within this picture, numerous companies are forming partnerships and joint ventures to prepare for emissions capture, transport, and storage.

- **NEE:** Russia shows no real commitment to reducing emissions (CAT, 2022). Kazakhstan's 2060 carbon neutrality strategy (2023) mentions CCS but lacks specific targets. Ukraine's draft *National Energy and Climate Plan* for 2025 to 2030 includes long-term CCS plans but notes the research, knowledge, and technological base is still in its early stages (Energy Community, 2024).

Fiscal

- **CHN:** China offers low-cost funding via the People's Bank of China's Carbon Emission Reduction Facility. By 2025, the national ETS will expand to cover 60% of national emissions including steel, cement, and aluminium smelting industries (MOE, 2025), adding about 3 $GtCO_2$ emissions to the market (in addition to about 5 $GtCO_2$ from power). This is consistent with earlier signals of the inevitable expansion of the national carbon market to include high-emission industries. We project the regional average carbon price level will reach USD 20/tCO_2 by 2030, USD 40/tCO_2 by 2040, and USD 90/tCO_2 by 2050.

- **MEA:** There is limited explicit CP and fossil fuel subsidies are widespread. Interest in carbon markets is emerging, with KSA planning to launch a carbon credit exchange and Turkey's ETS currently in pilot phase. We project the regional average carbon price level will reach USD 10/tCO_2 by 2030, USD 20/tCO_2 by 2040, and USD 30/tCO_2 by 2050.

- **LAM:** Several economies are working on ETS development and some have carbon taxes at low levels. Uruguay is the exception in the region with high carbon taxes of USD 167/tCO_2. We project the regional average CP level will reach USD 10/tCO_2 by 2030, USD 25/tCO_2 by 2040, and USD 40/tCO_2 by 2050.

- **SEA:** Several countries (Indonesia, Malaysia, Thailand, Vietnam) are developing or expanding their CP schemes throughout the present decade. Singapore is the region's CP frontrunner with its carbon tax set for steady increase to 2030. We project the regional average will reach USD 10/tCO_2 by 2030, USD 30/tCO_2 by 2040, and USD 50/tCO_2 by 2050.

- **NEE:** CP adoption is slow across the region, with Kazakhstan and Ukraine maintaining low price levels in existing schemes. Ukraine's CP will strengthen if it joins the EU. In 2024, Ukraine enacted a climate policy law setting up an ETS framework to pilot in 2026 (EOS, 2025). We project the regional average carbon price level will reach USD 6/tCO_2 by 2030, USD 10/tCO_2 by 2040, and USD 20/tCO_2 by 2050.

Technology-push

- **CHN:** China has long funded research and pilot projects in major industrial sectors. Support will continue with the inclusion of GHG emissions control and CCS in the 2024 *Catalogue of green-transition-related industries* (GCCSI, 2024b). State-owned enterprises (SOEs) like Sinopec, Huaneng, and CNOOC are key players in piloting and demonstrating commercial-scale CCS projects and full chain developments that address the cross-chain risk.

- **MEA:** Government control over CCS value chains is strong in KSA, Qatar, and the UAE with state-owned entities like Saudi Aramco, Qatar Energy LNG, and ADNOC leading projects and full-chain development. Innovation in carbon management is also SOE funded, such as ADNOC's carbon conversion project (CCM, 2024) and KSA's Carbon Capture and Utilization Challenge (MEP, 2024). CCS focus is shifting from hydrocarbon production to include industry and low-carbon fuels. KSA and Italy's agreement to enhance energy cooperation (Argaam, 2025) is positioning Italy as a strategic entry point for green energy into Europe.

- **LAM:** Currently, there are no funding programmes or direct support for CCS investments. Funding may become available in the 2030s as Brazil's policies evolve, such as the *Neo-Industrialization Policy* with decarbonization plans up to 2033. We expect Brazil's CCS projects to focus on the energy sector (hydrocarbons) – driven in part by international oil companies' net-zero declarations – and bioenergy with carbon capture and storage (BECCS).

- **SEA:** There is a general lack of policy and funding for CCS outside the oil and gas sectors. Singapore launched a *Grant Programme for CCS Feasibility Studies* in October 2024 to co-fund CCS technologies in the power sector. Vietnam announced an initial CCS project plan for a coal-fired power plant in September 2024. Thailand's SOE, PTT Exploration & Production, announced a USD 2bn five-year investment plan (2024-2028) for cleaner energy that includes CCS (Battersby, 2024).

Demand-pull

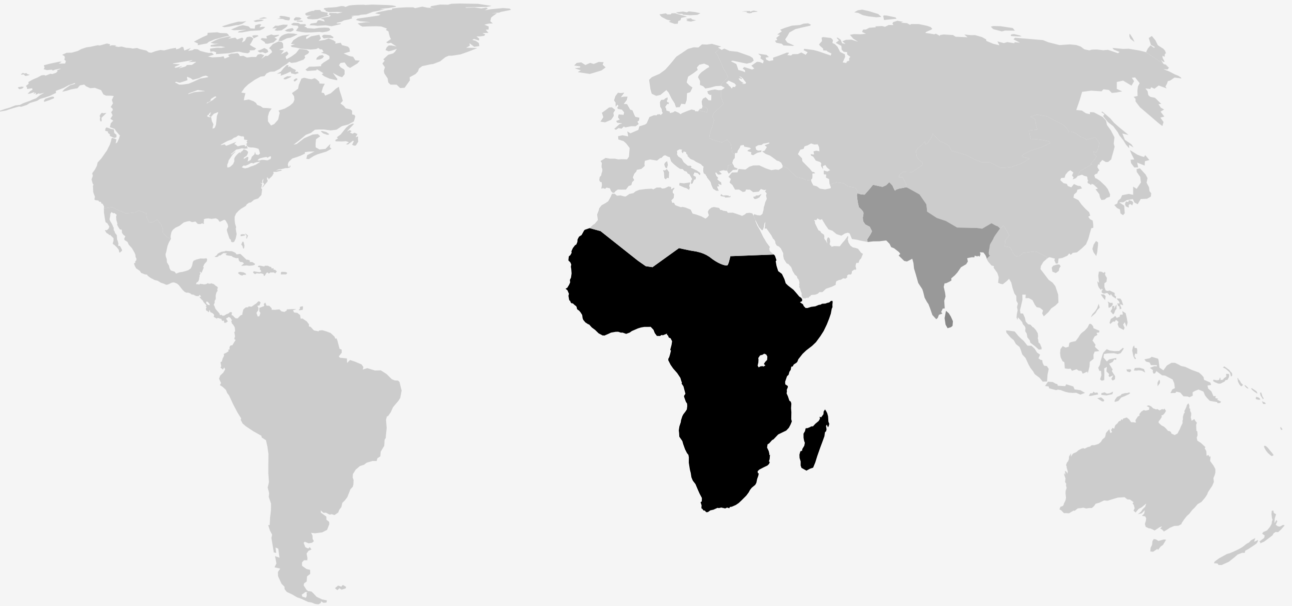
- **CHN:** CCS deployment will rely on mandates on SOEs, driven by the 2060 carbon neutrality ambition as well as carbon pricing. The updated *Coal Action Plan* aims to cut coal power emissions per KWh by 50% by 2027, nearing natural gas plant levels. This will be achieved through co-firing with at least 10% biomass or green ammonia, or using CCS technologies (Jia et al., 2024). Government support will back these projects.

- **MEA:** Net-zero targets and the presence of national oil companies – which bring economic resources, expertise, and existing infrastructure – will drive CCS scale-up in hard-to-decarbonize sectors and for converting hydrocarbon fuels to low-carbon alternatives.

- **OTHER REGIONS:** CCS deployment is hindered by insufficient regulatory frameworks and support, making it difficult to secure returns from CCS projects outside oil and gas.

Low-income regions

Sub-Saharan Africa (SSA)
Indian Subcontinent (IND)



Goals & Priorities

- **IND:** India aims for net-zero emissions by 2070 and leads the region in advancing CCS. It is developing policies based on the analysis of inter-ministerial planning body, NITI Aayog (NITI Aayog, 2022). These policies focus on cluster models, business model designs, and financial incentives for the CCS industry. While there is no official capture/storage target, NITI Aayog suggests a potential 750 $MtCO_2$/yr capture capacity by 2050.

- **SSA:** There is an absence of regulatory frameworks for CCS. Net-zero targets, conditional on international support, have been announced by Tanzania and South Africa by 2050, Ghana and Nigeria by 2060, and Uganda by 2065.

Fiscal

- **IND:** Explicit carbon pricing is limited. In 2023, India announced a domestic *Carbon Credit Trading Scheme* for energy-intensive sectors as an extension of the *PAT scheme*, likely starting with cement and launching by 2026. We project the regional average carbon price level will reach USD 10/tCO_2 by 2030, USD 25/tCO_2 by 2040, and USD 45/tCO_2 by 2050.

- **SSA:** Explicit carbon pricing is limited and adoption will be slow. South Africa has a carbon tax of about USD 10/tCO_2. Nigeria announced an ETS but implementation details are unclear. The Africa Carbon Markets Initiative aims to expand carbon credits projects for voluntary and compliance markets. We project the regional average carbon price level will reach USD 2/tCO_2 by 2030, USD 10/tCO_2 by 2040, and USD 20/tCO_2 by 2050.

Technology-push

- **IND:** In 2025, the government will launch 'Mission CCS' to develop an India-specific ecosystem and advance technology goals. Priorities include industrial applications and thermal power for clean baseload power. The mission will feature funding programmes, building on experience from the *Production Linked Incentive scheme* and Viability Gap Funding to capital costs (Kala, 2024). Challenges to CCS developments include cost and lack of infrastructure. India will pursue International funding avenues supporting CCS research and development, such as the *European Accelerating CCS Technologies* (ACT) initiative providing transnational funding.

- **SSA:** There are no public funding programmes for CCS-related development. South Africa is showing interest as part of reducing emissions from coal-fired power generation. Climeworks and Great Carbon Valley have proposed a 1 $MtCO_2$/yr DAC project in Kenya (Sharma, 2023).

Demand-pull

- **IND:** Current policy lacks concrete support mechanisms. To drive deployment, we expect India will develop demand-side policies like sector obligations, that leverage renewable energy policy experience. NITI Aayog (2022) recommended creating a Carbon Capture Finance Corporation (CCFC) to fund tax and cash credits (USD/tCO_2) to ensure project revenue streams with differentiation between EOR, storage, and utilization. Proposed rates are USD 49/tCO_2 until 2040 and USD 36/tCO_2 until 2050 for sequestration/storage; USD 36/tCO_2 until 2040 and USD 29/tCO_2 until 2050 for EOR; and USD 27/tCO_2 until 2050 for utilization.

- **SSA:** There is no concrete policy or support for deployment.

India leads the regions in advancing CCS. It is developing policies based on the analysis of inter-ministerial planning body, NITI Aayog.

4.2 SOCIETAL PUSHBACK AGAINST CCS

DNV's global *Energy Transition Outlook 2024* (DNV, 2024a) includes a comprehensive discussion of societal pushback against energy transition technologies. CCS projects also encounter societal pushback due to concerns about economic, environmental, safety, and perceived health impacts (see Section 3.1 for a detailed overview of safety considerations). Distrust in the stakeholders and processes, and interactions between stakeholders and affected communities, are also common factors leading to pushback. Additionally, CCS projects tend to receive more suspicion and apprehension due to scepticism about whether they will enable fossil fuel extraction to persist and the long-term efficacy of CCS technologies as a climate change mitigation measure.

Examples of projects affected by societal pushback

Societal pushback has been a factor in delaying and even cancelling CCS projects. Initiated in 2007, a pioneering project in Barendrecht, the Netherlands, aimed to capture CO_2 from a nearby refinery and store it onshore in depleted gas fields. Residents and politicians were worried about perceived risks, including CO_2 leaks, long-term environmental impacts, and the potential depreciation of property values (Akerboom et al., 2021). Residents felt the responses to these concerns were inadequate, and changes to the regulatory approval process further exacerbated opposition. The project was eventually cancelled in November 2010.

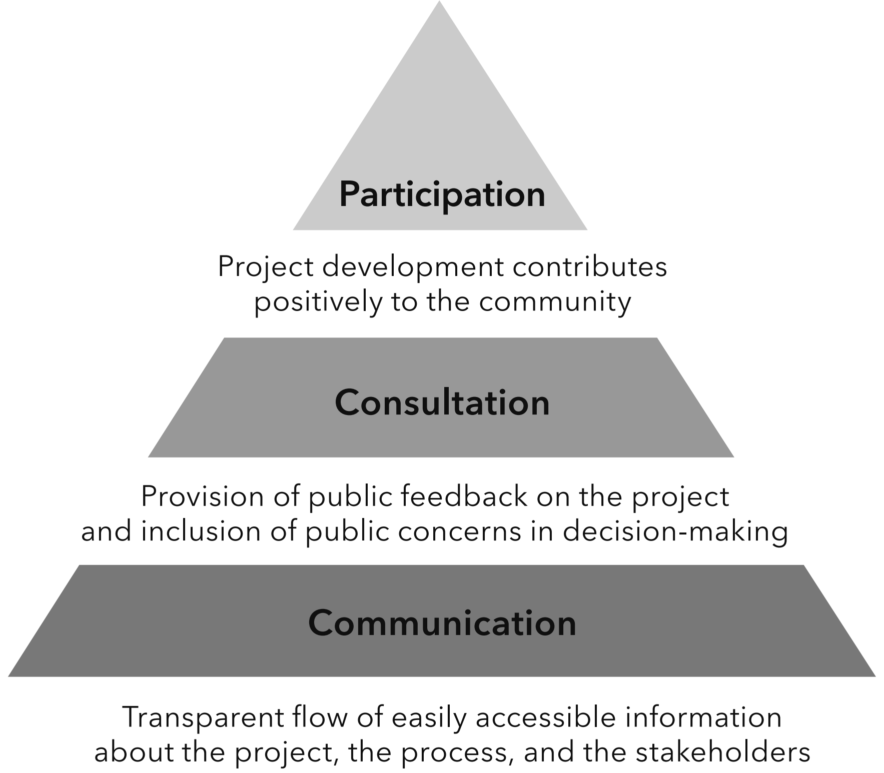
In 2021, the Heartland Greenway 2,000 km pipeline project was set to span five states in the US Midwest. The project planned to transport up to 15 MtCO_2/yr, captured from ethanol plants, for underground storage in Illinois. Local communities expressed strong resistance, citing concerns over land rights and environmental impacts. Due to strong community opposition, state officials in South Dakota and Iowa rejected the necessary permits. The combined impact of community-driven opposition and regulatory hurdles resulted in the project's cancellation in October 2023 (Lydersen, 2023).

Measures for mitigating community-based opposition

Like other transition technologies, CCS projects that engage locals and relevant stakeholders early and with measures that span the three pillars of energy justice are less likely to experience significant opposition from the community.

Energy justice framework

Distributional justice	Encompasses issues of equity: the fair distribution of benefits, burdens, and risks.
Justice as recognition	Concerns the fair involvement and recognition of those affected by energy developments.
Procedural justice	Comprises inclusion, fairness, and participation in decision-making processes.



Engagement types can be separated into three levels: basic (communication), intermediate (consultation), and advanced (participation). The levels of public engagement are cumulative; participation models include consultation measures which include communication. The advanced level of engagement with participatory measures is most useful for fostering public acceptance and successfully implementing energy projects. Participatory measures often include financial benefits, such as ongoing income streams from the project for local communities, typically through participatory business models.

The purpose of these measures is to build trust with the community and to assuage their uncertainties around real and perceived risks. All engagement measures must consider the social context in which they operate. Factors such as political system, regional income levels, local political landscape, and attitudes towards decarbonization will influence how a community will respond. Hence, we observe many more instances of pushback against CCS projects in countries which are democracies and considered high-income. These countries tend to have more formalized public engagement processes to allow for communities to voice their concerns. The relationship between societal acceptance and large infrastructure projects like CCS is complex and context dependent, where every project will have unique facets.