DNV

WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK
CCS TO 2050

Carbon capture and storage: from turning point in 2025 to scale by mid-century

FOREWORD

I am delighted to introduce this report on DNV's global forecast for CCS through to 2050. The reason for issuing this report now is that we believe CCS is at a turning point. The CCS project pipeline has grown significantly, and, in the next five years, we expect operational capacity to increase substantially.

The surge in installation reflects a widening appreciation of the decarbonization role of CCS. So far, the heavy lifting on carbon capture development has been done within oil and gas production – for natural gas processing and enhanced oil recovery. But after 2030, the market for CCS will increasingly address hard-to-decarbonize emission sources. With this shift, we forecast that North America will be joined by Europe as a leading region for CCS deployment.

In the hierarchy of emissions reduction strategies, the first consideration should always be energy efficiency. Next is the use of renewables to replace fossil energy sources. Finally, there is CCS, which occupies an increasingly important niche: tackling emissions in hard-to-decarbonize sectors. This includes CCS for process emissions in manufacturing, and in the production of low-carbon hydrogen from the steam reforming of natural gas.

Our forecast is that CCS will grow significantly: from 41 Mt/yr today to 1.3 Gt of CO_2 captured and stored in the year 2050. That is a big uplift, but it falls short of where CCS should be in a net-zero outcome. Furthermore, we forecast that energy-related emissions roughly halve from today to 2050, and so, ironically, it is in today's high-emitting world where CCS is best applied.

The biggest barrier to the very much needed acceleration of CCS deployment is policy uncertainty. Policy shifts, not technology or costs, have been responsible for many CCS project failures. However, policy support for CCS is firming across most world regions. Indeed, carbon markets and voluntary offsets will evolve to the point where even the more expensive carbon removal technologies such as direct air capture (DAC) will be widely deployed towards the end of our forecast period.

I remind readers that DNV's 'most likely' forecast of our energy system to 2050 is one associated with a dangerous 2.2°C of global warming by 2100. Yet, in this most likely future, we find that CCS will scale rapidly and will attract significant investment – some USD 700 billion over the next two-and-a-half decades, without taking into account onboard CCS for ships. However, in any net-zero future, orders of magnitude more CCS will be needed. DNV stands ready to work with customers worldwide to build safe and reliable CCS – faster.

Ditlev Engel

CEO

DNV Energy Systems

HIGHLIGHTS

1. The turning point for CCS has arrived, with capture and storage capacity expected to quadruple by 2030
2. After 2030, the strongest growth will be in hard-to-decarbonize sectors, with manufacturing accounting for 41% of annual CO_2 captured by mid-century
3. CCS will grow to capture 6% of global CO_2 emissions in 2050, which falls significantly short of what is required for any net-zero outcome
4. Carbon dioxide removal (CDR) will capture 330 $MtCO_2$ in 2050 – one-quarter of total captured emissions

Cover photo: Northern Pioneer CO_2 transport ship at Northern Lights receiving terminal in Øygarden, Norway. Photo: Ruben Soltvedt / Northern Lights.

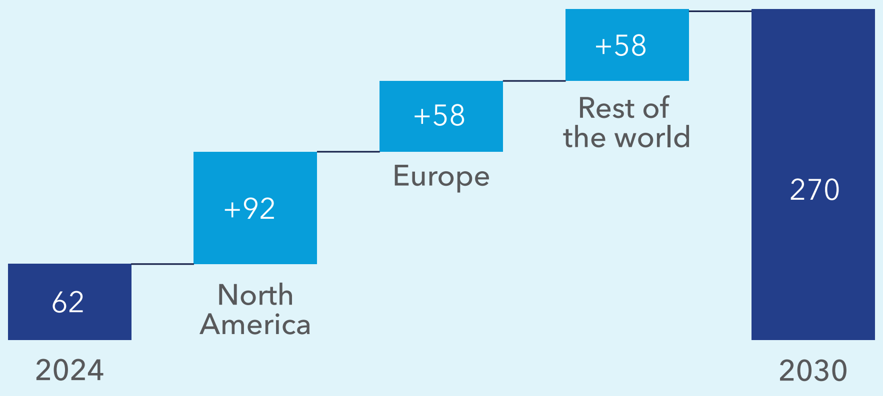
HIGHLIGHTS

1 The turning point for CCS has arrived, with capture and storage capacity expected to quadruple by 2030

- North America and Europe will drive this short-term scale up, with natural gas production still the main application. We will also see growth across many sectors and regions, including first-of-a-kind applications.
- Cumulative investments in CCS in the coming five years are expected to reach about USD 80bn.
- Global economic instability and budgetary pressures may pose risks to CCS deployment, potentially shifting priorities and removing finance needed.

CCS capacity additions to 2030

Units: $MtCO_2$/yr

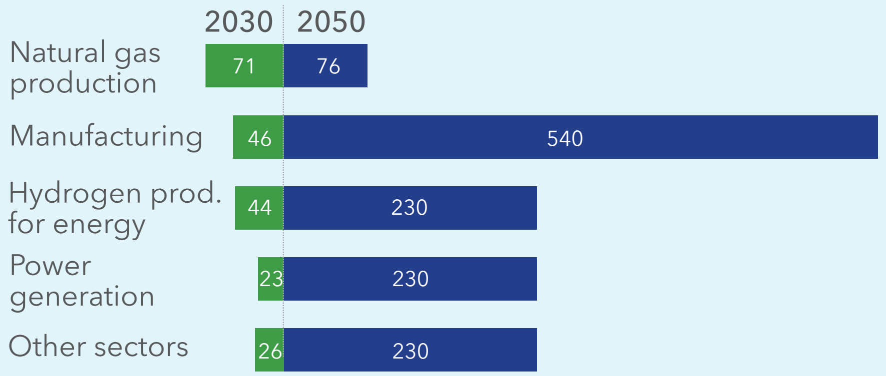


2 After 2030, the strongest growth will be in hard-to-decarbonize sectors, with manufacturing accounting for 41% of annual CO_2 captured by mid-century

- CCS is essential to address hard-to-decarbonize emissions from manufacturing sectors, like steel production, and from maritime transport, where onboard capture is expected from the 2040s in parts of the global shipping fleet.
- Manufacturing, particularly cement and chemicals, will be the biggest application of CCS in Europe; in North America and the Middle East it will be hydrogen and ammonia; in China, coal power.
- Although capture from natural gas production will continue, its share falls from 34% in 2030 to 6% of total capture in 2050.

CCS by sector in 2030 and 2050

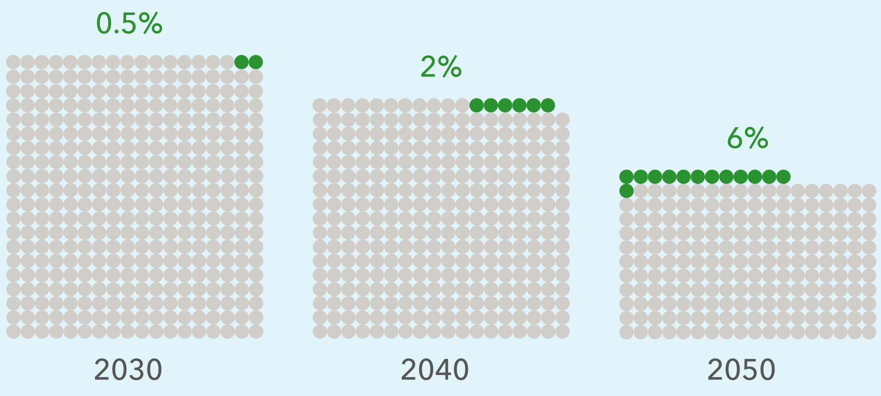
Units: $MtCO_2$/yr



3 CCS will grow to capture 6% of global CO_2 emissions in 2050; that falls significantly short of what is required for any net-zero outcome

- Uptake will grow from 41 $MtCO_2$/yr captured and stored today to 1,300 $MtCO_2$/yr in 2050.
- Despite positive policy and investment signals, CCS will need to scale to over six times the forecast level to reach DNV's Pathway to Net Zero Emissions. Scaling is particularly important in hard-to-decarbonize sectors.
- CCS is growing where there is policy support. In most sectors, it will only scale with mandates and price incentives. Europe has the strongest price incentives and will catch up with – and eventually surpass – current North American deployment dominance.
- Average costs will decline by around 40% towards 2050 as technologies mature and scale.

Share of global CO_2 emissions captured with CCS



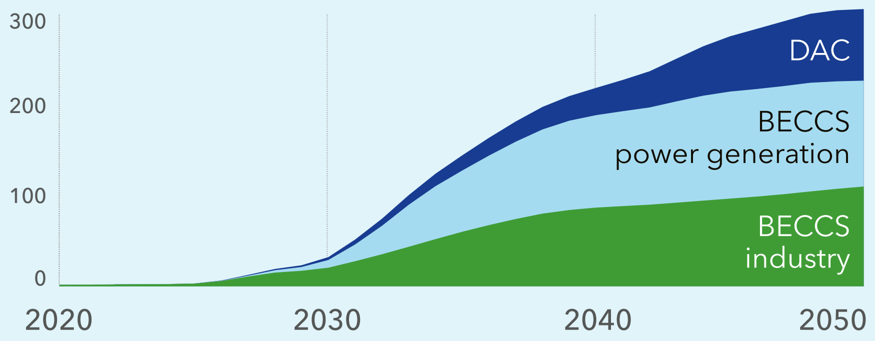
One circle represents 100 $MtCO_2$/yr. CCS numbers include carbon removal.

4 Carbon dioxide removal (CDR) will capture 330 $MtCO_2$ in 2050 – one-quarter of total captured emissions

- As global emissions continue to accumulate, CDR becomes important to reduce the large carbon budget overshoot.
- Bioenergy with CCS (BECCS) is generally the cheaper CDR option and will be used primarily in renewable biomass for power and manufacturing.
- Direct air capture (DAC) costs remain higher at around USD 350/tCO_2 through 2050, but voluntary and compliance carbon markets still ensure the capture of 32 $MtCO_2$ in 2040 and 84 $MtCO_2$ in 2050.
- Beyond our forecast period, an enormous amount of CDR, alongside nature-based solutions, will be required to ensure net-negative emissions.

Carbon dioxide removal through 2050 by sector

Units: $MtCO_2$/yr



CONTENTS

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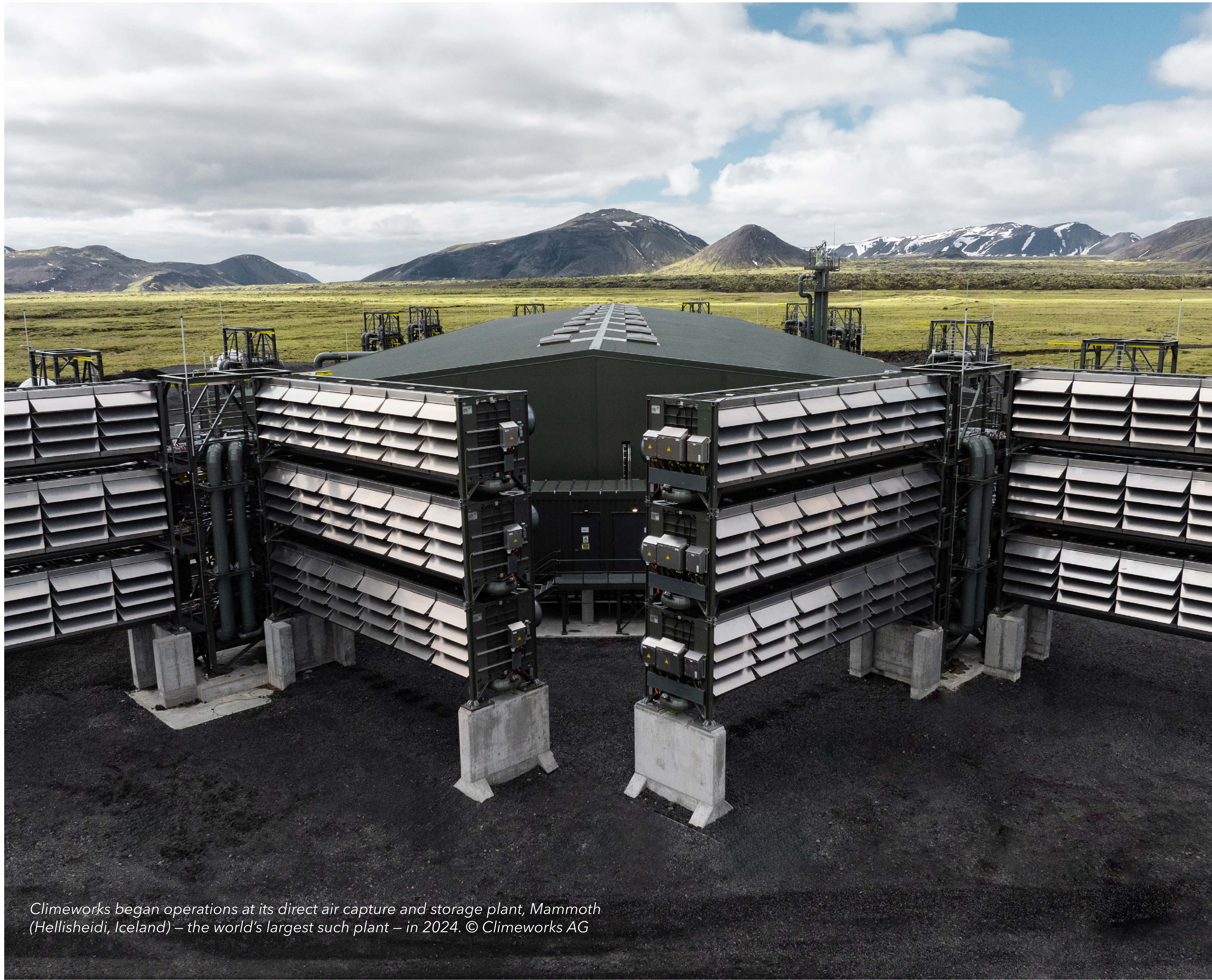
1 INTRODUCTION

This report is part of DNV's annual Energy Transition Outlook suite of publications and is our first dedicated global forecast for carbon capture and storage.



Climeworks began operations at its direct air capture and storage plant, Mammoth (Hellisheidi, Iceland) – the world's largest such plant – in 2024. © Climeworks AG

1 INTRODUCTION

Carbon capture and storage (CCS) is a suite of climate change mitigation technologies designed to capture CO_2 emissions, generally from flue or exhaust gases, to prevent their release into the atmosphere, and to safely store captured CO_2.

CCS involves three key steps:
1. Capture of CO_2 at the source of emissions
2. Transport of the captured CO_2 to a storage site
3. Storage of CO_2 in deep geological formations for permanent isolation.

In this report, we include carbon dioxide removal (CDR) technologies – such as direct air capture (DAC) of CO_2 – within the broader definition of CCS. While captured CO_2 can, in limited volumes, be put to productive use, giving rise to the term carbon capture, utilization, and storage (CCUS), the scale of such utilization remains relatively small. Therefore, we use the term CCS throughout this report, unless referring to utilization specifically.

In many cases, CCS builds on technologies that have been used commercially for decades. For instance, amine-based CO_2 capture has been successfully deployed at scale in coal-fired power plants and natural gas processing. In this sense, CCS is not a leap into the unknown; it simply repurposes existing industrial technologies for climate mitigation.

However, applying CCS across a wider range of sectors – such as aluminium smelting – presents new technical and economic challenges. Given the diversity of emission sources and gas compositions, it is necessary to adapt existing capture technologies and, in some cases, develop entirely new approaches.

There is broad international consensus – particularly among scientific bodies, climate experts, and major energy organizations – that CCS will play a vital role in a decarbonized energy future. This is especially true in hard-to-decarbonize sectors such as cement, steel, and chemical production, where CO_2 is emitted not just from fossil fuel use but as an inherent part of industrial processes. Since the release of the *IPCC Special Report on Carbon Dioxide Capture and Storage* (2005), CCS has consistently featured in scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and as an important part of DNV's own *Energy Transition Outlook* (ETO).

The purpose of this forecast is not to state what the scale of CCS in the 2050 energy system *should* be, but – in line with the forecast approach of the ETO – the scale it is *likely* to achieve.

Our approach

This report is part of DNV's annual ETO suite of publications. The CCS forecast to 2050 is derived from the ETO Model, which simulates the global energy transition across 10 world regions. As such, our CCS outlook is not a standalone assessment – it is embedded in a comprehensive, system-wide simulation that reflects the complex interdependencies shaping both global and regional energy landscapes. Further details on our modeling approach and assumptions are available in the main ETO 2024 report (DNV, 2024a).

Unlike most energy forecasters, DNV does not develop multiple future scenarios. Instead, we provide a single 'best-estimate' forecast that represents the most likely trajectory of the energy system, based on expected policy developments, technological progress, and cost trends. While we do explore key uncertainties and sensitivities, this approach avoids presenting potentially unrealistic futures – enabling us to focus on actionable insights. The key principles guiding our methodology are illustrated below.

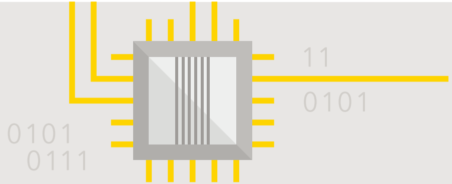
Chapter guide

Chapter 2 covers the technological and economic dimensions of the CCS value chain, examining each stage – capture, transport, and storage – in detail. Chapter 3 addresses the safety considerations associated with CCS, along with key technical challenges that may hinder its large-scale deployment. Chapter 4 describes the policy landscape and business models most likely to support CCS deployment. It also examines the critical issues of public acceptance, and the evolving regulatory frameworks needed to enable scale-up. Finally, Chapter 5 presents the results of our CCS deployment modeling, offering quantitative insights into the most likely uptake through to 2050.

Our **best estimate**, not the future we want

A single forecast, not scenarios

Long-term dynamics, not short-term imbalances



Continued development of proven **technology**, not uncertain breakthroughs

Main **policy** trends included; caution on untested commitments, e.g. NDCs, etc.

Behavioural changes: some assumptions made, e.g. linked to a changing environment

2 TECHNOLOGIES AND COSTS

CCS technology is not new. Carbon capture has been deployed in natural gas processing for decades, and CO_2 has been transported by pipelines since the 1970s and ships since the 1980s. But many new applications of CCS technology are emerging, which pose new technical and economic challenges.

This chapter details the technological and cost considerations for each stage of the CCS value chain – capture, transport, and storage – and includes a deep dive into onboard carbon capture, direct air capture (DAC), and CO_2 utilization. Coordinating the entire CCS value chain for optimization is also covered.

The Petra Nova carbon capture facility (shown on the right of this image) retrofitted at NRG Energy's W. A. Parish coal-fired power plant in Texas. Image: RM VM published under creative commons license CC-BY-SA-4.0

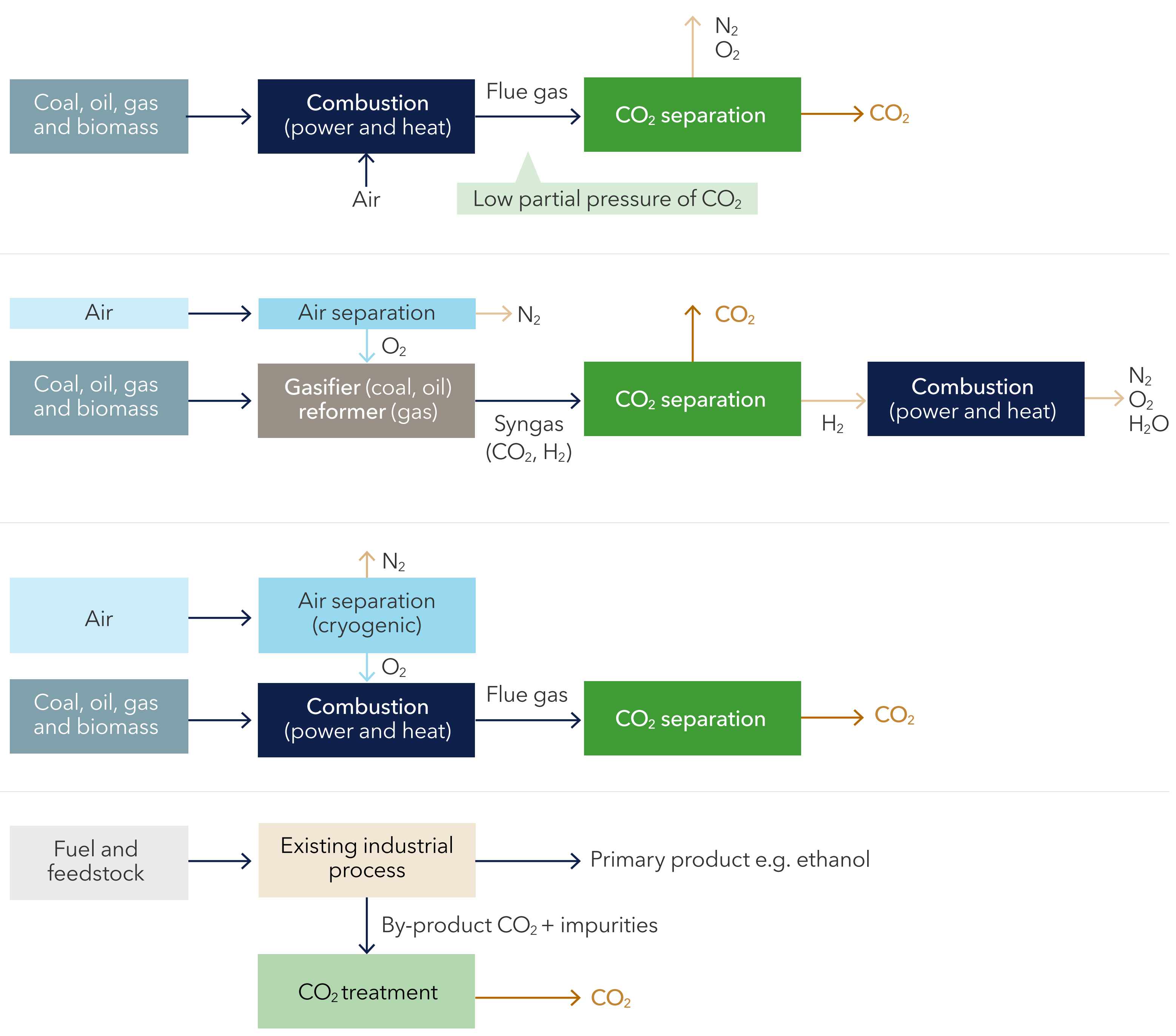
2.1 CAPTURE

Carbon capture is the process of separating and removing CO_2 from other components in a mixed gas stream. In point source capture, CO_2 is removed from the exhaust or flue gases produced by major emission sources – for example power generation or cement production facilities – capturing industrial emissions at the source. DAC, on the other hand, removes CO_2 from ambient air and is a negative emission technology. DAC is described further in the fact box on page 13.

Currently, 62 $MtCO_2$/yr of operational capture capacity is installed. This is supported by a strong development pipeline including many first-of-a-kind applications of capture technology. For instance, coupling CCS with dispatchable gas power generation to produce predictable low-carbon baseload power to supplement variable renewables generation. This approach is planned in the UK's NZT Power project, which reached a final investment decision in 2024 (Net Zero Teesside, 2024). The term carbon capture often includes other processing steps such as flue gas pre-treatment, purification of captured CO_2, compression and/or liquefaction, and integration of the capture facility with the host emitter site.

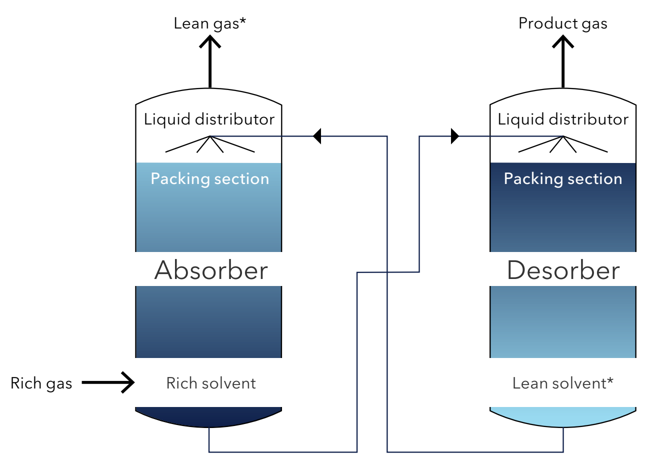
Four families of point source capture applications

Point source capture technology	Application
Post-combustion Capture from exhaust gases of combustion processes such as power generation, generally with a low CO_2 concentration.	– Coal- and biomass-fired power plants – Gas turbines – Industrial facilities – Waste-to-energy plants
Pre-combustion Capture before combustion, often at elevated operating pressure, for example natural gas processing or hydrogen production.	– Integrated Gasifier Combined Cycles (IGCC) – Hydrogen production – steam methane reforming
Oxy-combustion CO_2 capture from a combustion process using pure oxygen instead of air, giving a higher CO_2 concentration.	– Coal- and biomass-fired power plants – Gas turbines (Allam Cycle) – Industrial facilities (glass, cement)
Inherent capture Certain industrial processes already produce CO_2 as a by-product, typically at high concentration with minimal processing required.	– Ethanol production – Biomethane production – Ammonia production



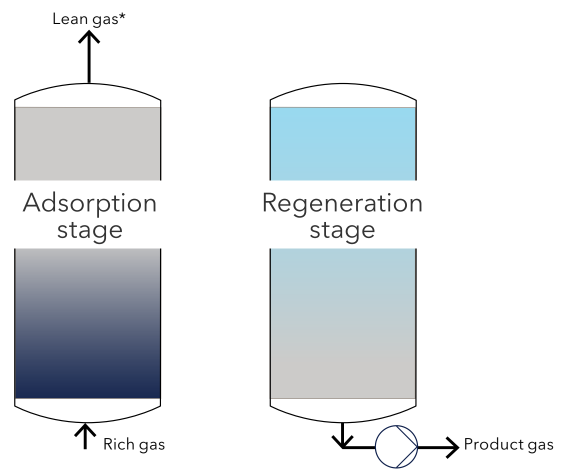
Four main families of capture technology

Absorption



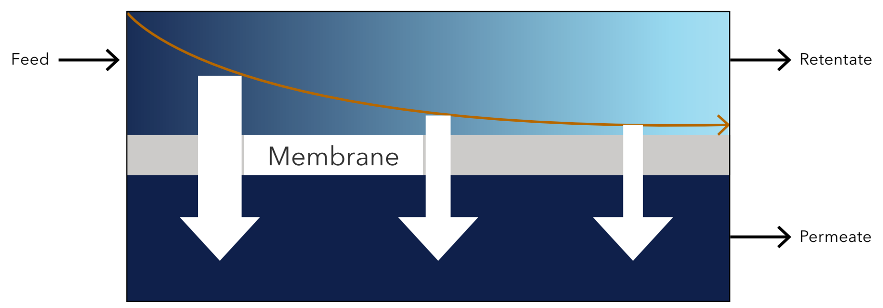
In **absorption**, CO_2 is selectively removed by physical or chemical interaction with a regenerable liquid solvent solution, including amine, non-amine chemical, and physical solvents.

Adsorption



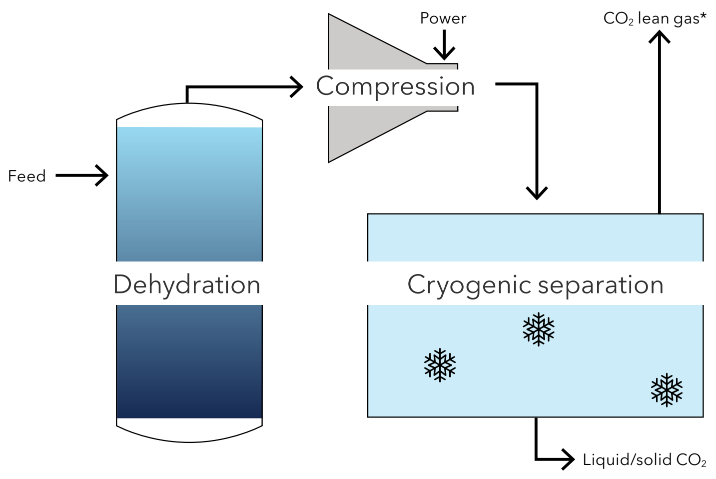
In **adsorption**, CO_2 is selectively trapped on the surface of a solid material through chemical or physical bonds before thermal- or pressure-driven regeneration of the solid material.

Membrane



Membrane capture uses materials which selectively allow CO_2 to permeate through a thin barrier medium under the influence of a driving force such as a pressure difference.

Cryogenic



Cryogenic technologies separate CO_2 from other gases through differences in volatility by cooling to low temperatures.

*Very low CO_2 concentration

Point source capture: applications, maturity, and technologies

Point source capture can be deployed to decarbonize a wide range of industrial emission sources. These are grouped into post-combustion, pre-combustion, and oxy-combustion capture applications. Additionally, certain industrial processes, such as ethanol production, already inherently produce a high purity CO_2 by-product.

A range of technologies are used in carbon capture, often adapted from other common industrial gas separation processes that have an extensive track record of removing CO_2 from gas mixtures.

Capture technologies with narrower applications such as chemical looping, which uses metal oxide carriers to alter the combustion process, and industry-specific CO_2 capture technologies, such as Leilac for the cement industry (Hills, 2017), are also available. Ongoing research and development efforts are exploring novel capture approaches and hybrid systems that combine two or more capture technologies.

When assessing technical maturity, it is important to consider both the capture technology itself and the application in which it will be deployed.

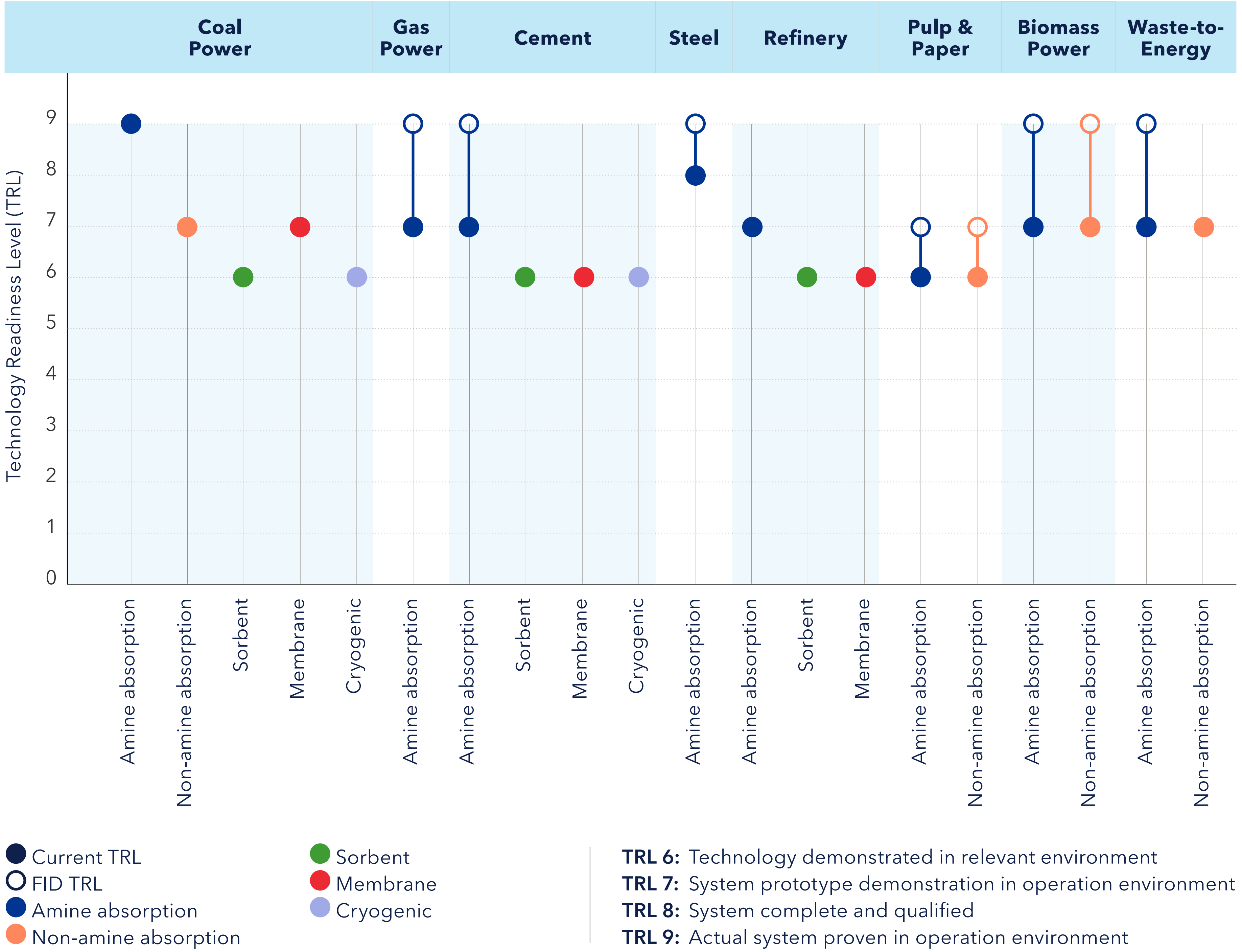
Brevik carbon capture facility at Heidelberg Materials cement plant in Brevik, Norway. Photo: Heidelberg Materials AG.

When assessing technical maturity, it is important to consider both the capture technology itself and the application in which it will be deployed. For example, amine absorption has been demonstrated at a commercial scale for coal power capture, but not on aluminium smelters, which present different technical challenges.

Amine absorption is the most mature technology for commercial scale carbon capture from most emission sources. However, concerns remain around the capital intensity, energy consumption, environmental impact, and solvent degradation of this technology.

Research and development efforts are focused on both improving amine technologies and maturing alternative capture technologies. A robust technology selection process is critical to successful capture projects. Key selection criteria such as flue gas characteristics, including CO_2 concentration and impurity levels, must be aligned with the operational envelope of the capture technology. Site characteristics – including availability of space and utility systems – must also be considered. For example, amine absorption systems require a low pressure steam for regeneration, which is more readily available in industries such as power generation than in others such as cement production.

The feasibility of capture technologies has been demonstrated in a variety of sectors



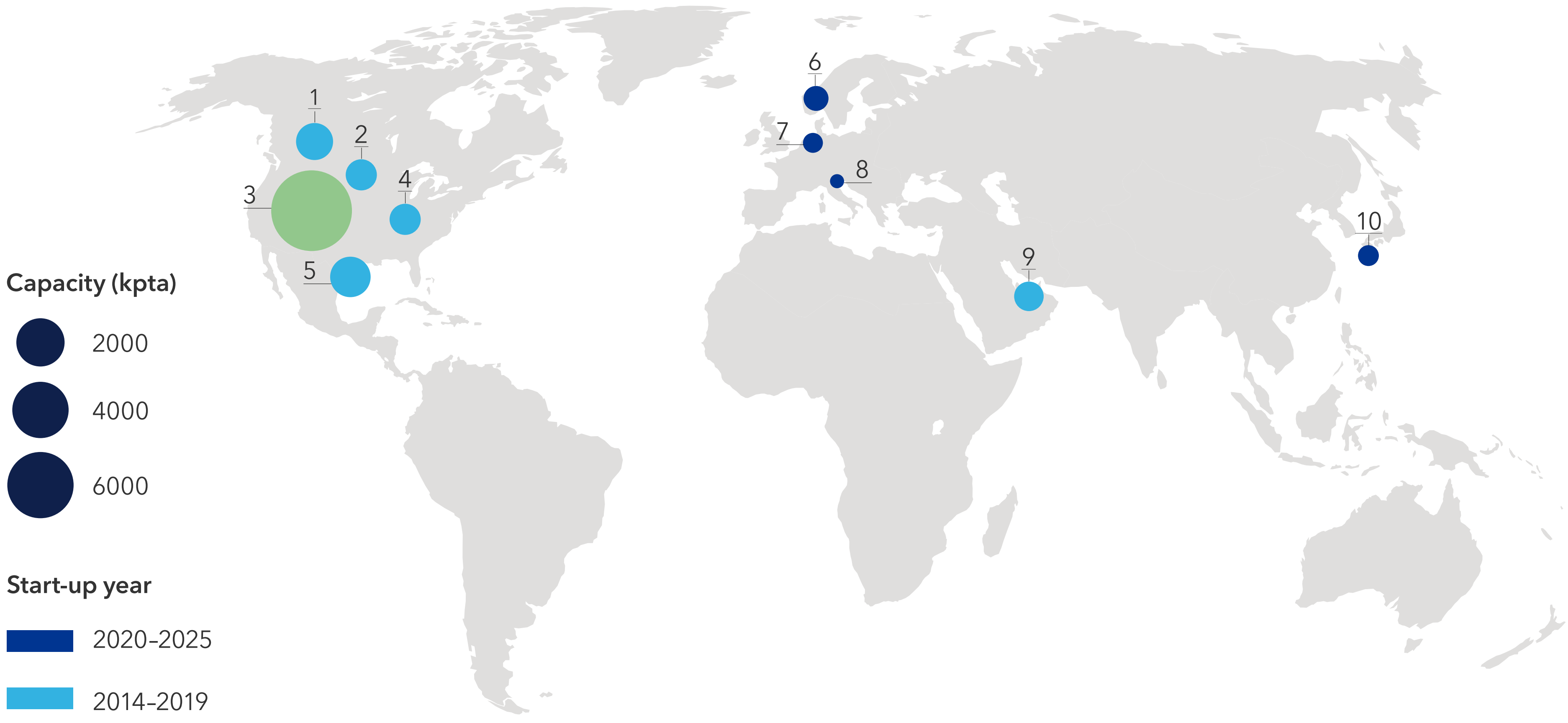
Technology readiness level as of Q1 2025.
Capture Technology Readiness Level by Application & Technology, EU H2020 TRL Scale.

Reference facilities

Selected operational capture reference facilities in various industries

Nr	Name and Location	Industry	Design Capacity (ktpa)	Technology	Start-up year
1	Quest, Canada	Hydrogen	1 200	Amine, Shell Adip-X	2015
2	Boundary Dam, Canada	Coal Power	1 000	Amine, Shell Cansolv	2014
3	Shute Creek, US	Natural Gas Processing	9 100	Physical Solvent, Selexol	1986
4	ADM Illinois, US	Ethanol	1 000	Inherent	2017
5	Petra Nova, US	Coal Power	1 700	Amine, MHI	2017
6	Heidelberg Materials Brevik, Norway	Cement	400	Amine, Capturi	2025 (in commissioning)
7	Twence, Netherlands	Waste-to-Energy	100	Amine, Capturi	2025
8	Ravenna, Italy	Gas Turbine	25	Amine, MHI	2024
9	Al Reyadah, UAE	Steel	800	Amine, MEA	2016
10	Mikawa, Japan	Biomass Energy	180	Amine, Toshiba	2020

Mature capture technologies have been deployed across various industries



Capture deployment and reference facilities
The majority of CO_2 capture deployment up to 2030 will utilize amine absorption capture technologies due to their relative maturity and established commercial-scale deployment in several industries. However, over the same period, we expect the market share of non-amine technologies to increase.

Recent trends show region-specific and industry-specific technology trends emerging, such as the use of hot potassium carbonate chemical absorption in Europe and cryogenic capture in the cement industry. Flagship operational or commissioning capture facilities in many common capture applications are summarized in the table above.

Capturing (industrial) biogenic CO_2 emissions, those that originate from the natural carbon cycle, uses identical capture technologies as fossil or process-based CO_2 emissions. This is known as bioenergy with CCS (BECCS) and is an important carbon dioxide removal (CDR) technology. BECCS is gaining significant momentum due to the revenue opportunities from credit generation in both compliance-driven and voluntary carbon markets. BECCS with ethanol production, supported by the 45Q tax credit (detailed in Section 4.1), is a rapid growth area in North America, while in Europe numerous BECCS projects are being developed at waste-to-energy, bioenergy, and biomethane facilities.

CO_2 capture can be complementary to other decarbonization measures, most notably through the production of low-carbon hydrogen. In this process, fossil-fuel-derived hydrogen, produced by natural gas reforming or coal gasification processes, is coupled with carbon capture to reduce the carbon intensity of the produced hydrogen. The Quest CCS project, operated by Shell in Canada, is a notable operational example. It uses a chemical solvent and has been operational since 2015 with a capacity of 1.4 MtCO_2/yr (Duong, 2019).

Reducing costs and delivering performance

CO_2 capture, as well as compression and liquefaction to prepare CO_2 for transport, are all energy-intensive processes. This is the largest contributor to the operating cost of a capture project, often referred to as the 'energy penalty'. The form and quantity of energy required will vary between technologies and applications. For example, amine capture systems require thermal energy to regenerate the solvent. This energy is often provided from fossil fuel sources and can decrease the net avoided CO_2 emissions.

The gap between CO_2 captured and CO_2 avoided can be reduced by including the energy source emissions within the boundary of the capture project or by implementing electrification, heat recovery, and energy efficiency measures to reduce the emission intensity of the energy source. Reducing the energy penalty remains a priority for capture technology development, and improvements in materials, processes, and site integration strategies all show promise.

The partial pressure and concentration of the CO_2 in the inlet stream are also primary cost drivers. Due to low chemical and physical driving forces, achieving very high capture rates (the percentage of CO_2 entering the capture system that is separated and removed) can require significant additional energy input and can also increase CAPEX through unit sizing.

Targeted capture rates have steadily increased over the last decade. A capture rate of 90% is now typically considered the minimum standard for point sources, with higher rates of 95% or above increasingly targeted. The UK *Dispatchable Power Agreement* business model for CCS in gas power generation is a recent example (BEIS, 2022). For current amine technologies, we expect no or modest cost increases when moving from a 90% to 95% capture rate, with some analysis even predicting marginally lower costs at 95% (NETL, 2022) (Global CCS Institute, 2025). However, costs will increase significantly and non-linearly as capture rates approach 100%, driven by substantial increases in the energy required to regenerate the solvent. This is demonstrated at pilot scale with the CESAR1 solvent (Morlando, 2024; Benquet, 2021).

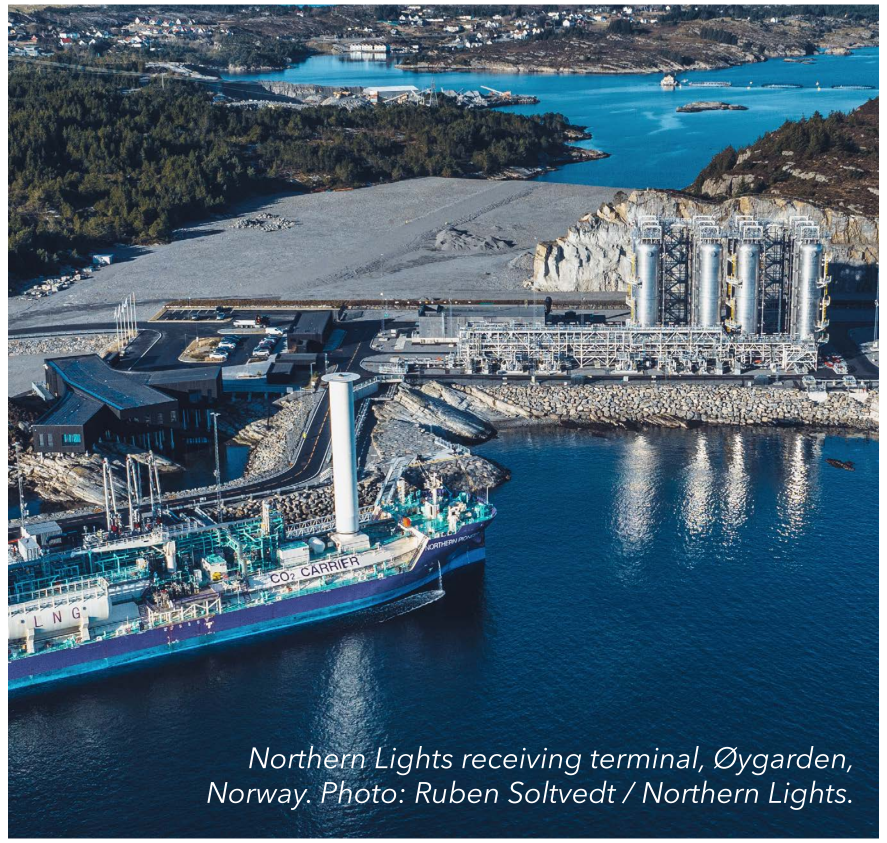
Modularization is an increasingly popular pathway for capture cost reduction. Modular plants use standardized designs and parts, are constructed off site, and can be scaled up by replication. This reduces costs and project delivery times through economies of scale, supply chain simplification, and transferable experience. This trend is currently most prevalent in amine absorption technologies but is also expected to help accelerate the maturation of alternative technologies, such as adsorption and membrane capture.

Capture technologies can be applied in both retrofit and new-build applications. Retrofit applications can benefit from existing infrastructure in some cases, but often face challenges with footprint, integration complexity, and parasitic loads on the host emitter facility. Building CCS into new facilities also has benefits, including heat recovery opportunities, where excess heat from one process is utilized in another. However, new-build applications may face increased total investment costs, lengthy permitting processes, and increased public scrutiny.

Connecting capture and transport

To ensure the integrity and efficiency of CO_2 transport and storage networks, capture plants must achieve a particular CO_2 purity specification that often requires additional treatment and purification. The purity of the CO_2 stream produced by capture systems is typically above 90 mol% CO_2, with some technologies able to achieve far higher purities. However, trace impurities from the flue gas and the capture process can still be present. These can pose integrity risks and operational challenges to CO_2 transport and storage networks.

Achieving the required purity specification almost always requires additional CO_2 treatment and purification. While treatment units for dehydration and oxygen removal are widely demonstrated in other gas processing industries, challenges remain in the online measurement of CO_2 quality and the removal of other impurities such as NO_X.



Northern Lights receiving terminal, Øygarden, Norway. Photo: Ruben Soltvedt / Northern Lights.

At the interface between the capture system and the transport and storage network, CO_2 must be compressed and/or liquified. The required phase and conditions of the product CO_2 will depend on the transport network type. CO_2 compression has been demonstrated widely in North America both in enhanced oil recovery (EOR) networks and in commercial-scale capture facilities such as Petra Nova (1.7 MtCO_2/yr). Commercial-scale liquefaction is less mature, and typically more expensive due to the need for additional equipment such as purification units and liquid buffer storage. The Heidelberg Materials Brevik cement capture project, currently in commissioning, will demonstrate liquefaction for transport by ship at a scale of 0.4 MtCO_2/yr.

Direct Air Capture (DAC)

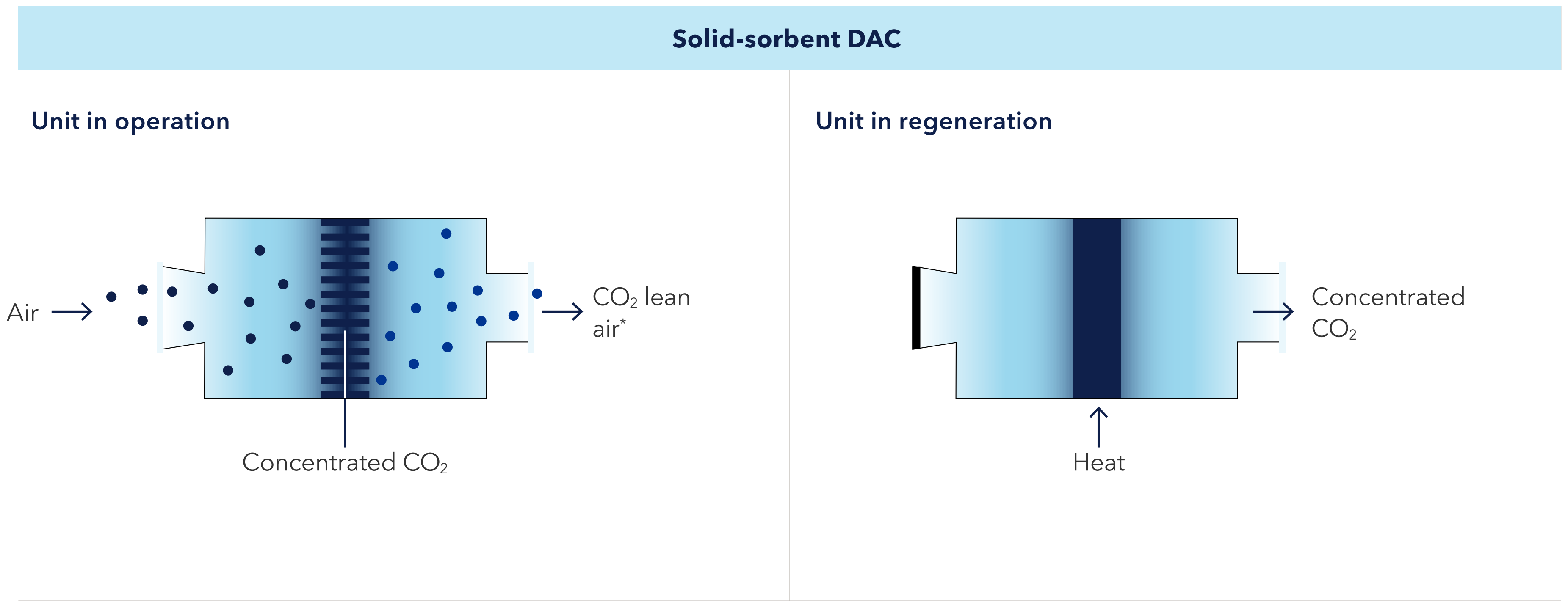
Solid-sorbent, liquid-solvent, and emerging DAC technologies
DAC is a promising CDR technology due to its flexibility and ability to remove CO_2 directly from the air. Two leading DAC technologies are readily scalable: solid-sorbent and liquid-solvent DAC (IEA, 2022). In the solid-sorbent method, solid adsorbents selectively capture CO_2 from the air, which is then released using changes in temperature, pressure, or humidity. The sorbent is regenerated at 80–120°C with minimal degradation, enabling continuous reuse.

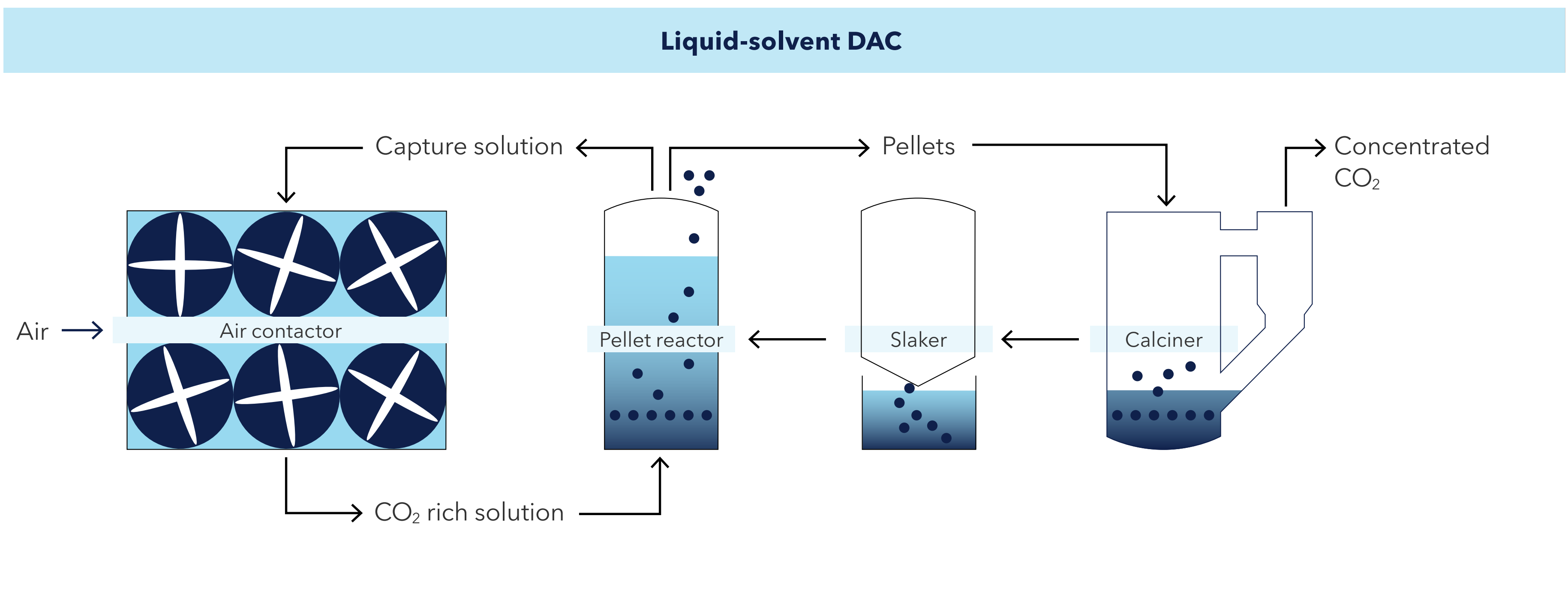
The liquid-solvent method uses strong hydroxide solutions (e.g. potassium hydroxide) to absorb CO_2, which then reacts with calcium to form calcium carbonate. To release CO_2, high temperatures (900°C) are required.

Several emerging DAC technologies are in the early stages of development, such as electro-swing adsorption (Voskian et al., 2019) and membrane-based separation (Fujikawa et al., 2022). These emerging approaches offer certain advantages to help solve several challenges of traditional DAC technologies. For example, electro-swing adsorption directly uses electrons for sorbent regeneration, potentially yielding higher energy efficiencies. However, many emerging DAC techniques have only been tested in laboratory settings and have lower technology readiness levels (TRL).

DAC is a promising CDR technology due to its flexibility and ability to remove CO_2 directly from the air.

Schematic of solid-sorbent DAC and liquid-solvent DAC





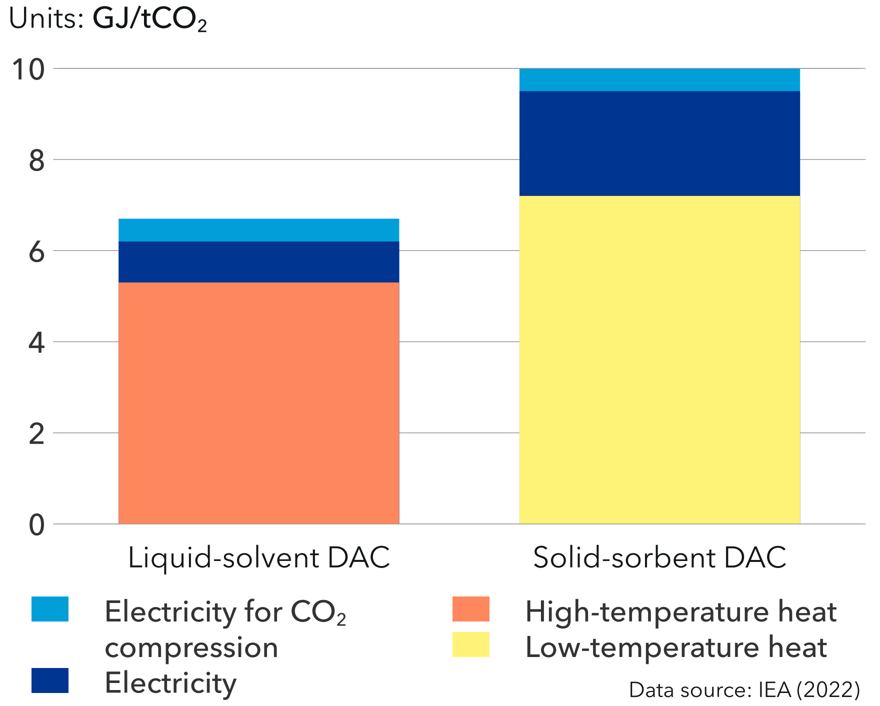
Air is drawn into the collector where the CO_2 is captured by a filter. Once the filter is saturated, the collector is closed and heated to release the captured CO_2 (regeneration). *Very low CO_2 concentration.

Energy requirements

One of the main challenges with DAC is the amount of energy required due to the low concentration of CO_2 in the atmosphere. Most DAC technologies require both electricity and heat (Figure 2.1). Electricity is needed for the fans to pull the air through the system, for pumps, CO_2 treatment, and to operate other auxiliaries. Heat is required for the desorption in solid-sorbent DAC and to regenerate the solvent for liquid-solvent DAC. For solid-sorbent DAC, which requires relatively low temperatures, it is possible to use a variety of renewable energy sources. For liquid-solvent DAC, on the other hand, natural gas or hydrogen are currently the main options for the heat supply. However, researchers are developing ways to electrify the calcination process.

FIGURE 2.1

Energy use of DAC



Data source: IEA (2022)

Carbon balance

The source of heat and electricity will influence the carbon removal efficiency or the net flux of carbon. If renewable electricity is used, carbon removal efficiency can be up to 97% (IEA, 2022). However, if natural gas is used without capturing the CO_2, carbon removal efficiency can drop to 60% (IEA, 2022).

Water balance

DAC plants can both produce and consume water. For solid-sorbent DAC, many of the adsorbents have an affinity for water, so they capture water along with CO_2. In both solid-sorbent and liquid-solvent DAC, the amount of water produced depends on the humidity of the air. In dry areas, water will evaporate in the liquid-solvent contactors, leading to a water deficit that needs to be replenished. In humid areas, the situation will be the reverse, i.e. water accumulates in the system and needs to be removed through evaporation.

Land use

The footprint of DAC will depend on the layout. While the collectors require space between them, this can be used for other purposes. The current land use estimates for capturing 1 $MtCO_2$/yr from air for liquid-solvent DAC is around 0.4 km^2, while a solid-sorbent DAC facility would require 0.9 km^2 (Webb et al., 2023). If the source of energy is included, the footprint could increase substantially.

Scalability and cost reduction

Different DAC technologies require distinct approaches to scaling up. Solid-sorbent DAC, which has a modular design, benefits from economies of volume manufacturing, where mass production of smaller units reduces costs over time. Further research and development on high-efficiency sorbent materials – e.g. metal-organic frameworks (MOFs) and porous polymers – with improved CO_2 capture and reduced degradation is crucial to the adoption of solid-sorbent DAC at scale.

In contrast, centralized DAC plants, like liquid-solvent DAC, rely on economies of scale, where larger facilities lower costs by processing higher volumes of CO_2 more efficiently. As DAC adoption grows, continued innovation and optimization will be crucial to improving affordability and accessibility.

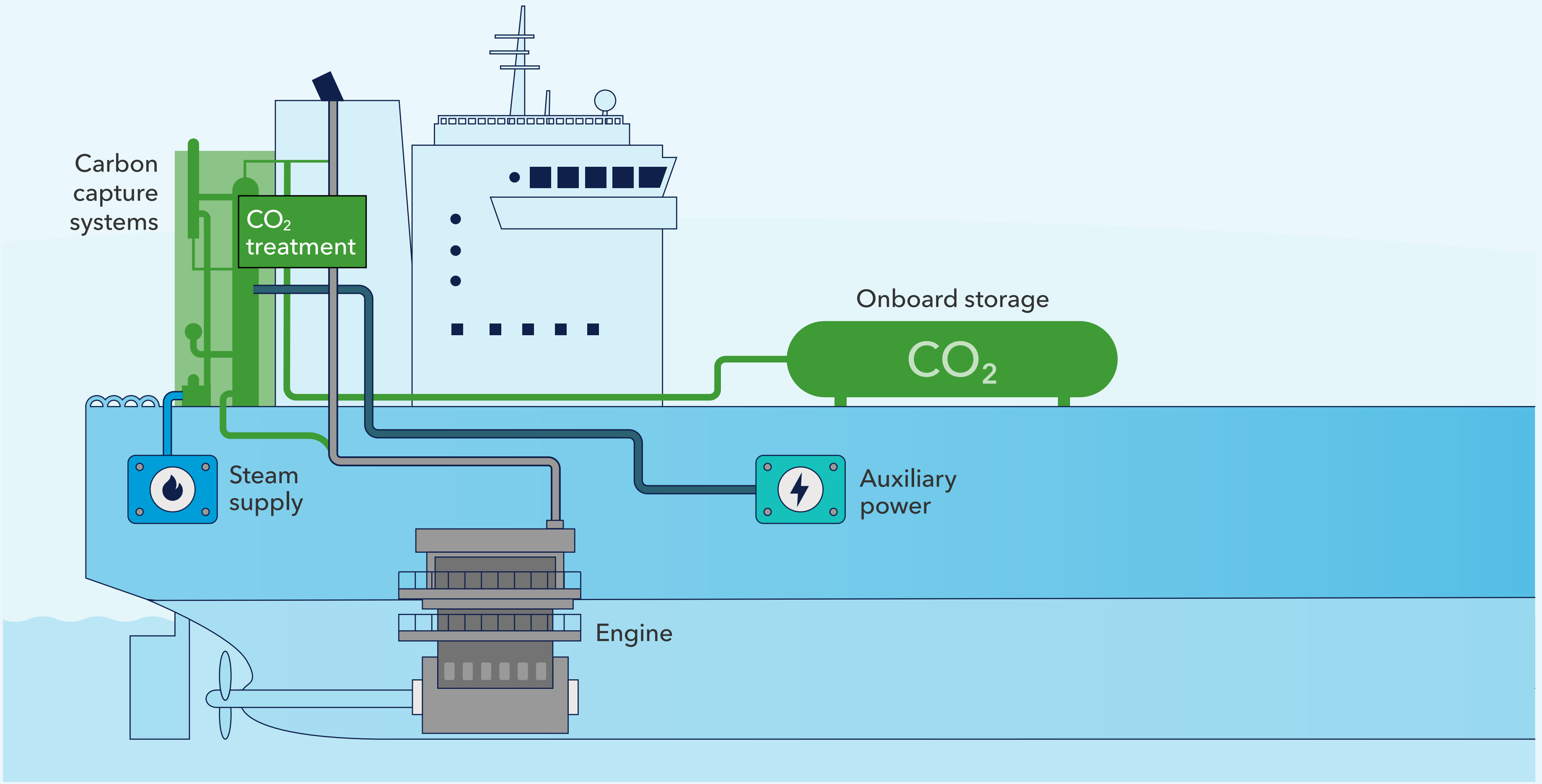
Climeworks' direct air capture and storage plant in Iceland. © 2024 Climeworks AG.

Onboard CCS

While many efforts to reduce greenhouse gas (GHG) emissions from shipping focus on switching to carbon-neutral fuels, another option is to capture the CO_2 produced by carbon-based fuels – whether fossil or carbon-neutral – and store it underground or use it in industrial processes approved by emission regulations.

Onboard carbon capture is based on technology that captures the carbon in the ship exhaust gas before it is emitted into the atmosphere. This can lead to significant emission reductions but requires additional energy and storage space.

Simplified subsystems in an onboard carbon capture system



The key technical and practical factors that affect the feasibility of onboard carbon capture for a dedicated ship are: size, operational profile / trading pattern, the machinery capacity for power and heat production, and the space available. One way to balance the trade-off between high capture rate and low fuel penalty (the additional fuel required to operate the capture system) is to optimize the capture rate according to the ship's operational profile and the availability of CO_2 offloading facilities along the way. Capture technology integration with the rest of the ship machinery system is essential to enhance the overall performance and reduce the fuel penalty. For newbuilds, the system can be optimized to minimize fuel consumption and to accommodate the system to the ship. Not all existing ships will be relevant candidates for retrofits due to the space and heat required to operate the system.

The application and uptake of onboard carbon capture technology on vessels is dependent on cost and price factors such as the capital costs of the system, fuel penalty level, operating costs, loss of cargo carrying capacity, and CO_2 discharge and storage costs, as well as economic factors like carbon pricing and fuel prices. Uptake also depends on the establishment of infrastructure for discharge and safe storage of CO_2 on a global (or regional) level.

Regulatory factors will also influence uptake. Today, only the EU Emissions Trading System (ETS) has adopted a regulatory framework that provides incentives for the use of carbon capture on board ships. However, the International Maritime Organization's MEPC 83 agreed to a work plan for the development of a regulatory framework for the use of onboard carbon capture. The work is set to be finalized in 2028 (IMO, 2025). The EU will also consider including onboard carbon capture in the next review of the *FuelEU Maritime* regulations (DNV, 2024b).

The *Maritime Forecast to 2050* (DNV, 2023a) evaluated the commercial feasibility of onboard carbon capture against carbon-neutral fuel alternatives for a 15,000 TEU container vessel. The study compared four fuel strategies (fuel oil, LNG, methanol, and ammonia) against onboard carbon capture with a 70% capture rate. The case study showed that onboard carbon capture was economically viable for a low-cost scenario (15% fuel penalty and deposit cost of USD 40/tCO_2) and competitive for a high-cost scenario (30% fuel penalty and deposit cost of USD 80/tCO_2)

For more information regarding onboard carbon capture, see DNV's whitepaper *The potential of onboard carbon capture in shipping* (DNV, 2024b).

2.2 TRANSPORT

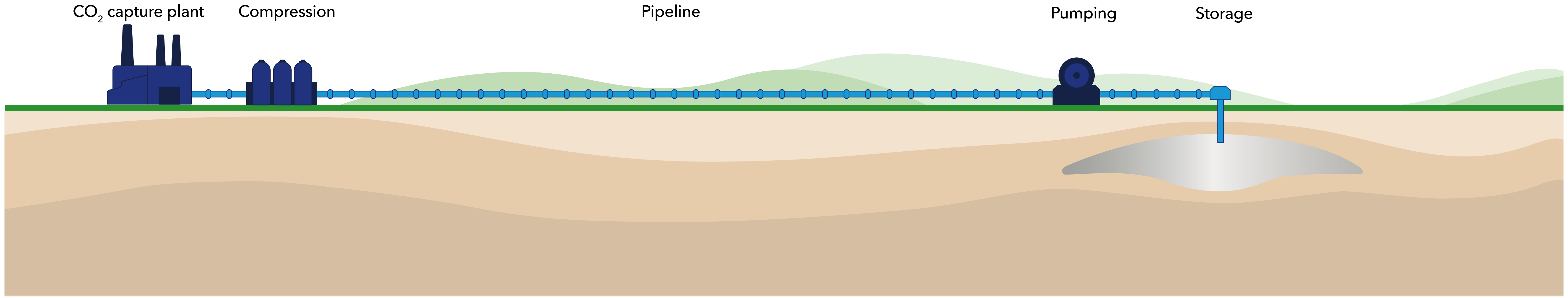
CO_2 transport is a critical component of the CCS value chain. It can be accomplished through pipelines, ships, trains, and trucks. Each method presents unique challenges that must be assessed based on parameters such as distance, terrain, and mass flow rate. In some situations, a multimodal approach that combines two or more transport methods offers the most effective solution.

Pipelines

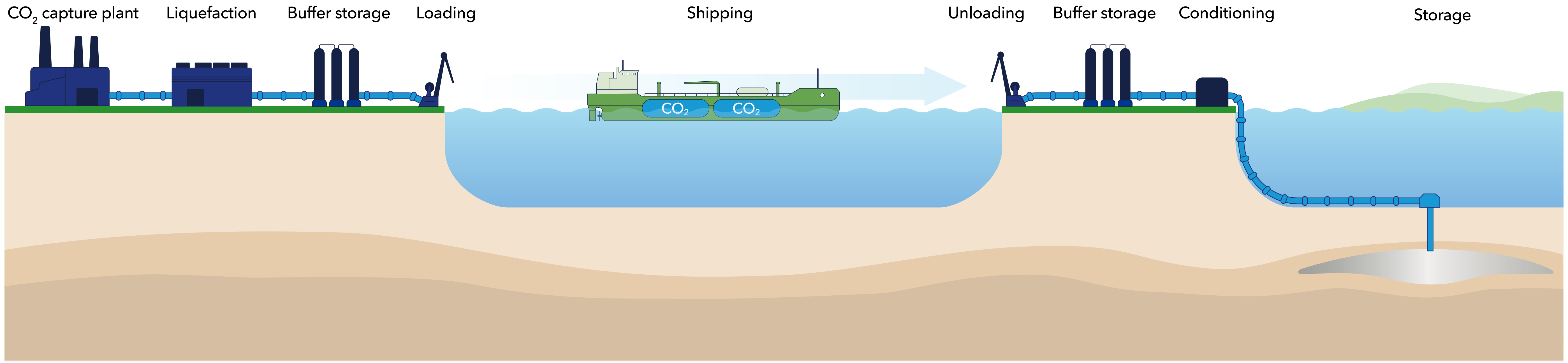
Pipelines have been used to transport CO_2 since the 1970s in the US, primarily for EOR purposes. Over 8,000 km of CO_2 pipelines are operational in the US today, making this a well-established technology. The typical pipeline value chain is relatively simple, involving the compression of CO_2 and the pipeline infrastructure itself.

There are two different conditions under which CO_2 can be transported: dense phase and gas phase. Dense phase transport (where CO_2 is maintained either in liquid or supercritical state), is preferred for high-volume, long-distance applications. Gas phase transport is generally employed for specific applications such as repurposed pipelines, early-stage operations with lower volumes, or certain onshore applications like those in urban areas. International standards generally recommend maintaining CO_2 entirely in either dense or gas phase during pipeline transport. Since temperature control is limited, pressure becomes the primary means to achieve the

Pipeline value chain



Shipping value chain (shore-to-shore configuration)



necessary thermodynamic conditions: dense phase operations typically require pressures above 80 bar, while gas phase conditions are maintained below 50 bar, depending on ambient temperature.

Shipping

Shipping CO_2 in the liquid phase for the food and beverage industry has been practiced since the late 1980s, but in considerably smaller volumes than will be relevant for CCS.

A ship-based CCS infrastructure is different to a pipeline infrastructure largely due to the fact that ship-based CO_2 transport occurs in batches. This leads to some key implications. First, CO_2 must be transported in liquid form to minimize volume and reduce the ship size required. Second, buffer storage is essential to accumulate sufficient volumes of CO_2 for the ship capacity and logistics.

As a result, the shipping value chain is more complex than pipeline transport. It generally requires a liquefaction unit, buffer storage at both departure and arrival points, specialized vessels, and usually an additional conditioning stage before final storage. The CO_2 can either be transported to a shore-based terminal or to an offshore facility where it is injected either into the reservoir directly from the ship or through a moored or fixed offshore structure.

An alternative option to carrying the CO_2 in a liquid state may be to transport it as dry ice. This could allow for the utilization of existing logistics infrastructure such as containers. However, this would also impact the rest of the CCS infrastructure.

Shipping CO_2 is often categorized in terms of operating and design pressure – low pressure, medium pressure, and high pressure. The pressure regimes have different temperatures, pressures, and density (Table 2.1). These regimes influence the ship design and liquefaction and conditioning costs, which ultimately impact the overall costs. The required ship size for the given trade and length of the voyage is a key factor in selecting pressure. Low pressure value chains generally allow for larger cargo tanks and larger vessels, which reduces shipping costs compared to medium pressure. The main benefit of high pressure is the reduced cost for liquefaction and conditioning. With a high-pressure vessel, however, the cargo containment system will be heavier and the density of the CO_2 is lower than for lower pressure conditions (low/medium pressure and low temperature).

TABLE 2.1
Pressure and temperature regimes for liquid CO_2 cargo tank designs[a]

Cargo designation	Cargo vapour pressure (operation) bara	Equilibrium temperature[a] °C	Density of liquid CO_2[a] kg/m³	Density of vapour CO_2[a] kg/m³
Low pressure	5.7 to 10	-54.3 to -40.1	1 170 to 1 117	15 to 26
Medium pressure	14 to 19	-30.5 to -21.2	1 078 to 1 037	36 to 50
High pressure	40 and above	5.3 and above	894 and lower	116 and higher

[a] Applies for pure CO_2 and properties taken from National Institute of Standards and Technology (NIST) database. Properties will depend on the other components in the CO_2 stream.

Source: International Organization for Standardization (2024)

Trains and trucks

For small-scale projects or scenarios with pre-existing infrastructure, trains or trucks can be viable transport solutions. Trains produce lower emissions but are limited by fixed infrastructure. In contrast, trucks provide greater operational flexibility but tend to generate higher emissions. Trains and trucks feature a value chain very similar to the ship-based one: they both make use of insulated but not refrigerated tanks and usually transport under low or medium pressure regimes.

Overall, the choice of transport method is dictated by a combination of technical, economic, and logistical factors. As the CCS sector continues to evolve, we see a variety of transport solutions being adopted. In some cases, multiple modes of transport will be used within a single value chain.

CO_2 transport ship, Northern Pathfinder. Photo: Northern Lights.

2.3 STORAGE

CO_2 storage requires the injection of CO_2 deep underground, where it must remain permanently. The most common and efficient method of permanent CO_2 storage is within basins comprised of sedimentary rocks. There are two main types of storage settings within such basins:

1. Depleted oil and gas fields
2. Deep saline aquifers

Repurposing depleted oil and gas fields for permanent CO_2 storage offers several advantages. These locations have proven subsurface traps and seals that have already retained hydrocarbon accumulations for millions of years and they are well-characterized after years of exploration, appraisal, and operation. This provides operators with extensive knowledge that reduces uncertainty regarding capacity, injectivity, and containment. Existing infrastructure can also be repurposed. For example, hydrocarbon production wells can sometimes be converted into CO_2 injection wells, potentially reducing costs. However, any repurposed infrastructure must be suitable beyond the operational life for which it was originally designed and be compatible with CO_2.

Depleted fields also present challenges for CO_2 storage including limited capacity, containment risks, and monitoring difficulties. The storage capacity of individual depleted fields is generally more limited than saline aquifer options. Injected CO_2 can fill the available pore space previously occupied by trapped hydrocarbon accumulations, but years of hydrocarbon production may have negatively impacted the reservoir and sealing formations and their suitability for CO_2 storage. The greatest CO_2 containment risk is also often attributed to pre-existing (legacy) wells, which represent potential leakage paths. If needed, remediating wells to ensure CO_2 compatibility and modifying platforms and pipelines can be costly. With respect to CO_2 monitoring, the residual hydrocarbons within the depleted field may inhibit the effectiveness of geophysical monitoring solutions, such as seismic surveys, making it more difficult to detect the injected CO_2.

The second type of storage is deep saline aquifers. These are underground formations composed of porous and permeable rocks saturated with water that is typically much saltier than seawater and unsuitable for drinking. An advantage of CO_2 storage in saline aquifers is that they have not been used for fossil fuel extraction except in cases where they share the same formation as neighbouring oil and gas fields and the subsurface environment (e.g. formation pressure) has been altered. Additionally, saline aquifer storage locations typically host fewer wellbore penetrations, which reduces the number of potential well-related leakage pathways. From a capacity standpoint, saline aquifers have greater flexibility because they represent a much larger segment of available pore space than oil and gas fields. Another benefit is that the feasibility of detecting and monitoring CO_2 injected into a saline aquifer using seismic surveys is generally better than in depleted field locations in which the CO_2 shares pore space with residual hydrocarbons. However, there are also disadvantages to consider. New infrastructure and storage wells will be necessary, which may increase costs compared with depleted field projects that repurpose infrastructure. Additionally, the storage performance of saline aquifers is initially less certain due to limited data availability from fewer wellbore penetrations and the lack of evidence that the intended trap and seal is viable. Such uncertainty can be mitigated through pilot projects, data collection, and testing at the beginning of the project and will continue to reduce over the project's lifespan.

Another way CO_2 can be stored underground is through CO_2 EOR. Although this is considered a form of utilization, much of the CO_2 remains trapped and permanently stored in the subsurface. EOR has

Storage projects

US: Saline aquifers account for approximately 80% of the total estimated geologic storage capacity in the US, whereas depleted hydrocarbon fields make up about 20% (NETL, 2015). However, 59% of the CO_2 captured from industrial processes and nearly all the CO_2 produced from natural sources (i.e. extracts from natural subsurface CO_2-bearing formations) are utilized for EOR in the US (EPA, 2021).

Europe: In some parts of Europe, there is a strong preference for saline aquifers near hydrocarbon fields (e.g. the proximity of the Northern Lights project in Norway to the Troll field), but storage potential in depleted fields exists as well (e.g. Greensand CCS project, Porthos CCS project, Aramis project).

APAC: A number of projects in this region are designed to store CO_2 in depleted hydrocarbon fields, including Duyong Petronas CCS in Malaysia, as well as Moomba Santos CCS and Angel Woodside CCS in Australia. Until recently, the SEA Exxon CCS project was among these (EPBC Act Public Portal, 2025), but it has been put on hold. On the other hand, the Gorgon CCS project (Chevron Gorgon CCS, 2025) has been storing CO_2 in a saline aquifer on Barrow Island in northwestern Australia since 2019. While it has faced criticism for not achieving targets, the project remains the largest commercial CCS project and CO_2 injection operation in the world.

been carried out mostly in the US and the Middle East since the 1970s, where injected CO_2 is used to extract additional oil from a mature field after the primary and secondary recovery methods have been exhausted. Produced CO_2 can then be separated from the oil and either recycled for continued EOR or vented. The experience gained from EOR has strengthened understanding of CO_2 storage in the subsurface, as well as the handling of large volumes of CO_2.

Carbfix on-site storage at Climeworks' Mammoth plant in Iceland. © 2024 Climeworks AG.

What about carbon mineralization?

Below-ground:
Carbfix in Iceland is pioneering a below-ground method of carbon storage known as 'in-situ CO_2 mineralization'. The captured CO_2 is first dissolved in water at the surface, to create a carbonated water solution. This solution is then injected into basaltic rock formations deep underground. Once in the basalt, the CO_2 reacts with minerals like calcium, magnesium, and iron to form stable carbonate minerals. This effectively turns the reacting CO_2 into solid minerals, permanently storing it within the rock. This method is particularly promising, but may be more difficult to implement and may benefit from more testing, since basaltic formations are less common than sedimentary rocks (i.e. those that host depleted oil and gas fields or saline aquifers).

Above-ground:
Above-ground carbon mineralization involves accelerating natural stable carbonate formation processes which result from CO_2 reactions with various minerals. There are three main types:

1. Ex-situ mineralization involves the production of carbonated aggregates, such as those used in low-carbon concrete. In this method, CO_2 is combined with an alkaline feedstock – e.g. mine tailings or industrial by-products – under high pressure and temperature to form stable carbonates.
2. Surficial mineralization occurs passively on land, coastlines, or oceans. CO_2 reacts with an alkaline feedstock, which is a basic, water-soluble material. The reaction can be accelerated by increasing the surface area of the mineral, e.g. by grinding certain rock-types into dust. This dust can be spread on agricultural soil, fields, forests, or along coastlines, where it reacts with CO_2 and stores it as carbonates.
3. Industrial by-product mineralization uses materials such as slag from steel production to capture and store CO_2. The by-products are treated with CO_2 to form stable carbonates, effectively sequestering the carbon and repurposing waste materials.

At present, the most efficient method for storing large volumes of CO_2 is permanent subsurface storage in geological formations, such as depleted fields and deep saline aquifers.

The experience gained from EOR has strengthened understanding of CO_2 storage in the subsurface, as well as the handling of large volumes of CO_2.

2.4 COSTS

The CCS industry is shifting towards a model where emitters are primarily responsible for capture facilities and will pay dedicated operators a tariff to oversee CO_2 transport and storage. The reasons behind this trend will be explored in more detail in Section 2.5.

Capture

Capture costs per tonne of CO_2 vary widely, reflecting the large range of applications in which it can be used. Factors influencing capture costs include CO_2 concentration, the scale of the capture facility, the transport method, and site-specific conditions.

It is important to distinguish between the cost of CO_2 captured (COC) and the cost of CO_2 avoided (COA) (i.e. the cost of reducing a tonne of CO_2 emissions, considering the entire system). These can differ significantly due to the emissions related to operating the capture plant, such as regeneration energy. The COA considers the net emissions reduction and will be higher than the COC: for example, around 25% higher according to a US study on a gas power plant (NETL, 2022). This conversion from COC to COA depends on both the energy demand and the carbon intensity of the energy source. As this varies widely between projects and regions, the COC is examined in this section.

The concentration or partial pressure of CO_2 within the gas stream entering the capture plant is an important cost driver because it influences the type of capture technology and the type and size of process equipment selected. Typically, higher CO_2 concentrations will deliver lower capture costs. For example, capturing CO_2 from bioethanol production costs USD 30 to 36/tCO_2 (greater than 90 mol% CO_2), compared to USD 60 to 120/tCO_2 from power generation (3-15 mol% CO_2) (IEA, 2020).

The scale of the capture facility also impacts costs. Larger facilities can leverage economies of scale, reducing process equipment capital cost. This is particularly important for low CO_2 concentration applications that process large volumes of flue gas. A study by the Global CCS Institute found that natural gas power (4 mol% CO_2) capture costs decreased from USD 120/tCO_2 to USD 75/tCO_2 as capture capacity increased from 0.07 to 0.66 MtCO_2/yr (Global CCS Institute, 2025). Operating costs, often dominated by energy consumption, tend to scale more linearly with capture capacity.

> It is important to distinguish between cost of CO_2 captured (COC) and cost of CO_2 avoided (COA).

The recent trend towards modular capture systems (Section 2.1) may offer a different cost relationship compared to bespoke capture plant designs. Standardized modular units could reduce costs for small-to-medium scale plants, but as capture capacity increases, we expect costs to scale more linearly. This is because increased capture capacities are achieved by replicating modular units. Other site-specific factors influencing capture costs include whether the capture plant is being retrofitted to an existing facility or is part of a new build project, the availability of utilities such as steam and cooling water, and regional labour and material market prices.

We expect capture plants producing liquefied CO_2 to be transported by ship, rail, or truck to incur higher capture costs than those compressing CO_2 for pipeline transport. This is because of the additional equipment requirements, including liquid buffer storage, and higher energy consumption.

Energy is typically the dominant operating cost in capture processes, with capture technologies requiring significant amounts of heat, electricity, or both. The main pathways to reduce energy OPEX are process and material improvements and enhanced site integration, such as waste-heat recovery from warm flue gasses.

In most CCS value chains, we expect capture to carry higher costs than transport and storage. The exceptions to this trend include cases with complex multimodal transport concepts or with very low capture costs, such as those with high CO_2 concentration flue gases typical of bioethanol production.

Transport

Accurate cost calculations for CO_2 transport facilities are impossible for a general case because transport costs tend to increase with the distance between the emitter and the storage site, the volume, the selected transport method, and other parameters. Nevertheless, a reasonable cost for compression and pipeline transport may range from USD 6 to 28/tCO_2, while transport by ship, train, and truck tend to suffer somewhat higher costs. In addition, pipeline transport is largely CAPEX driven, while train and truck transport is largely OPEX driven. Ship transportation has a more balanced split between CAPEX and OPEX. Usually, when multiple solutions are viable, the choice is made based on economic considerations.

Transport costs vary significantly depending on several factors such as transport mode, distance, fluid phase (gas/dense), mass flow rate, terrain, and region. Although transport costs will be project specific, there are some general trends.

The transport method is a key cost driver. This choice will be driven by a combination of the economic, technical, and regulatory factors discussed in Section 2.2. Generally, pipeline transport is more cost effective for large volumes (several Mt/yr) of CO_2 over short-to-medium distances (up to a few hundred kilometres). Liquid CO_2 transport methods, such as shipping, are more cost efficient for longer distances, geographically dispersed emitters, and lower CO_2 volumes. Multimodal transport concepts will incur higher costs than single stage transport networks.

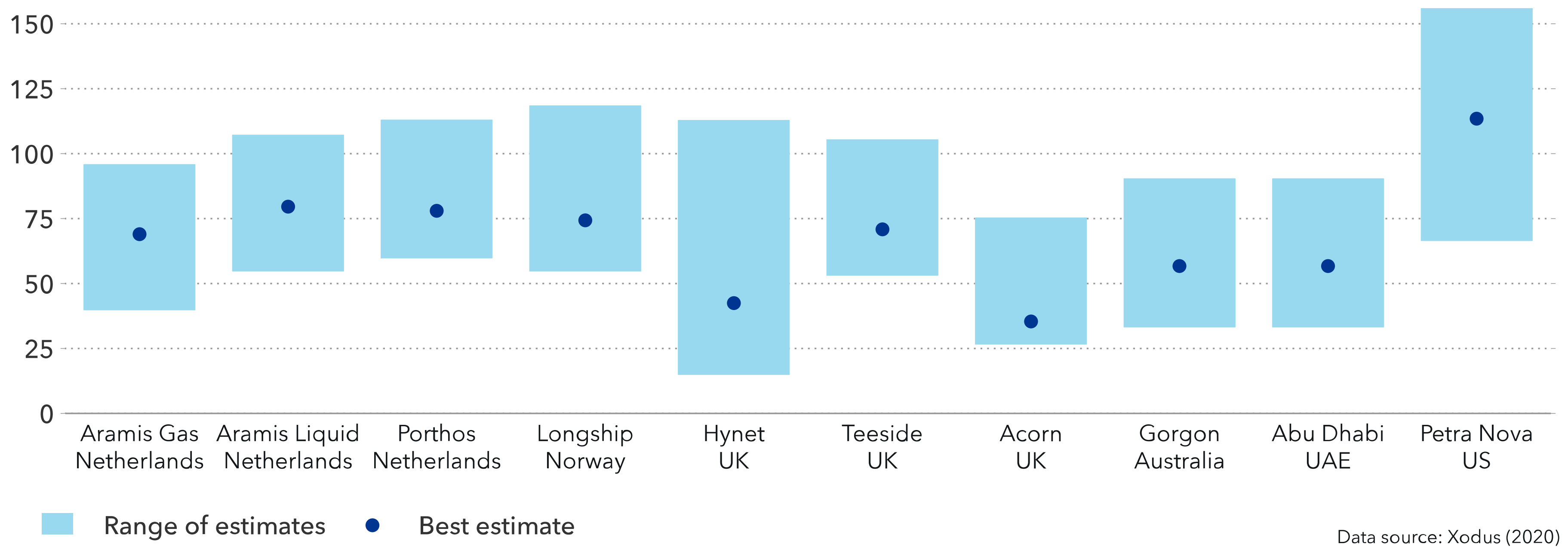
Pipeline transport benefits from economies of scale when mass flow rates increase, particularly in dense phase with higher fluid density when more CO_2 can be transported efficiently. While we anticipate a similar effect for ships, trains, and trucks, the need for additional vessels, railcars, or trucks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

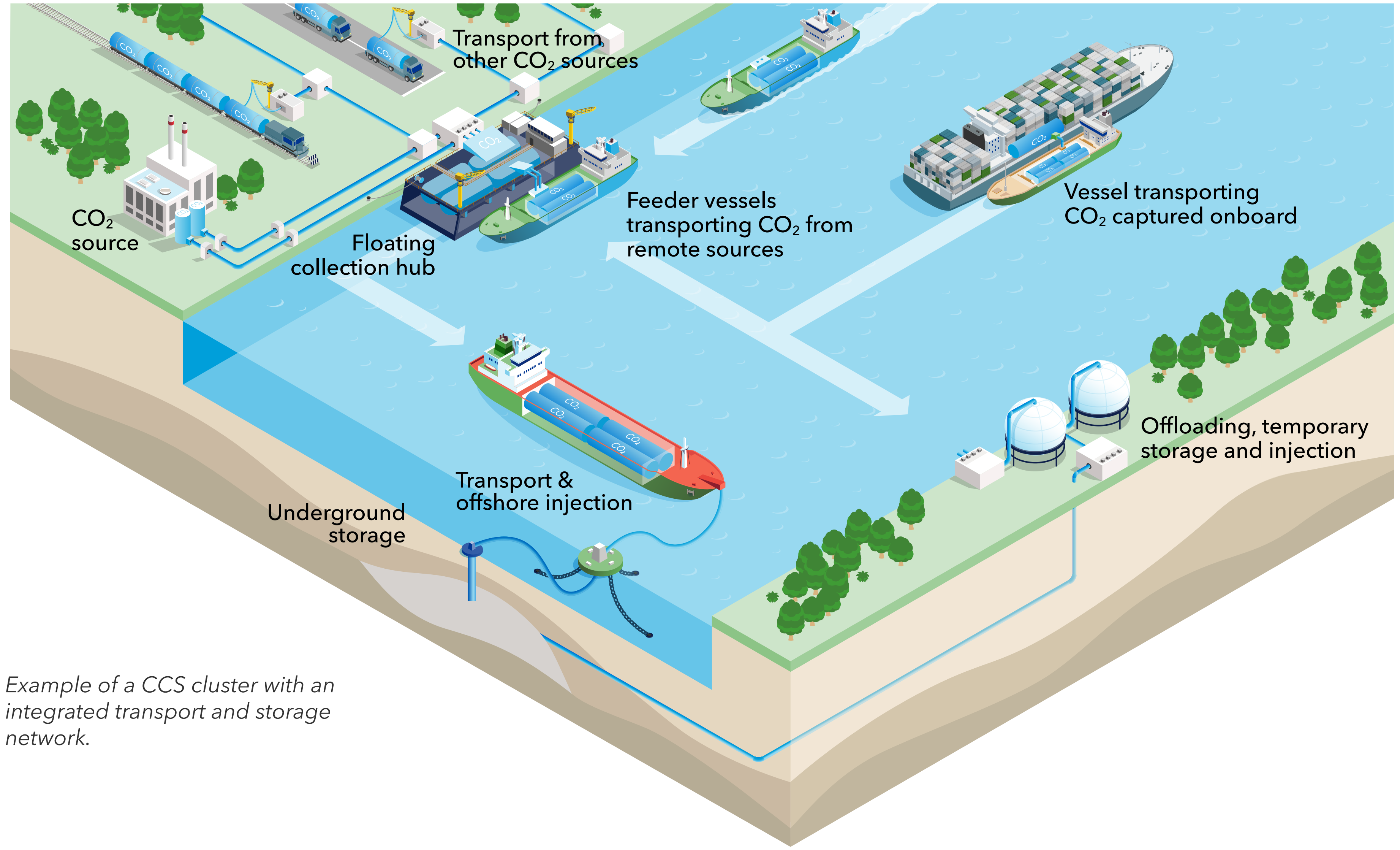
2.5 VALUE CHAIN

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.

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.



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

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

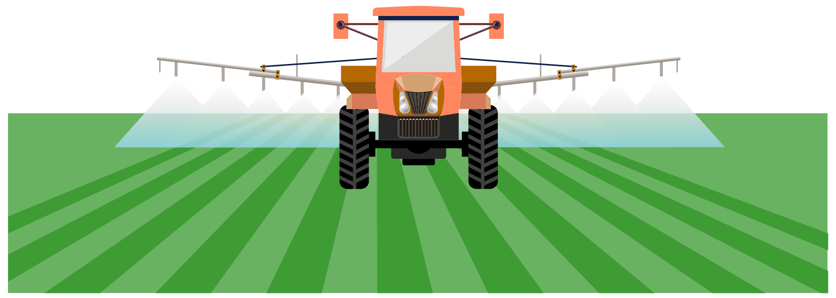
Emerging applications are gaining interest and projections suggest that by 2030, new pathways might capture an additional 15 $MtCO_2$ annually (IEA, 2019). Below are some of the leading applications among potential pathways of CO_2 conversion.

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.

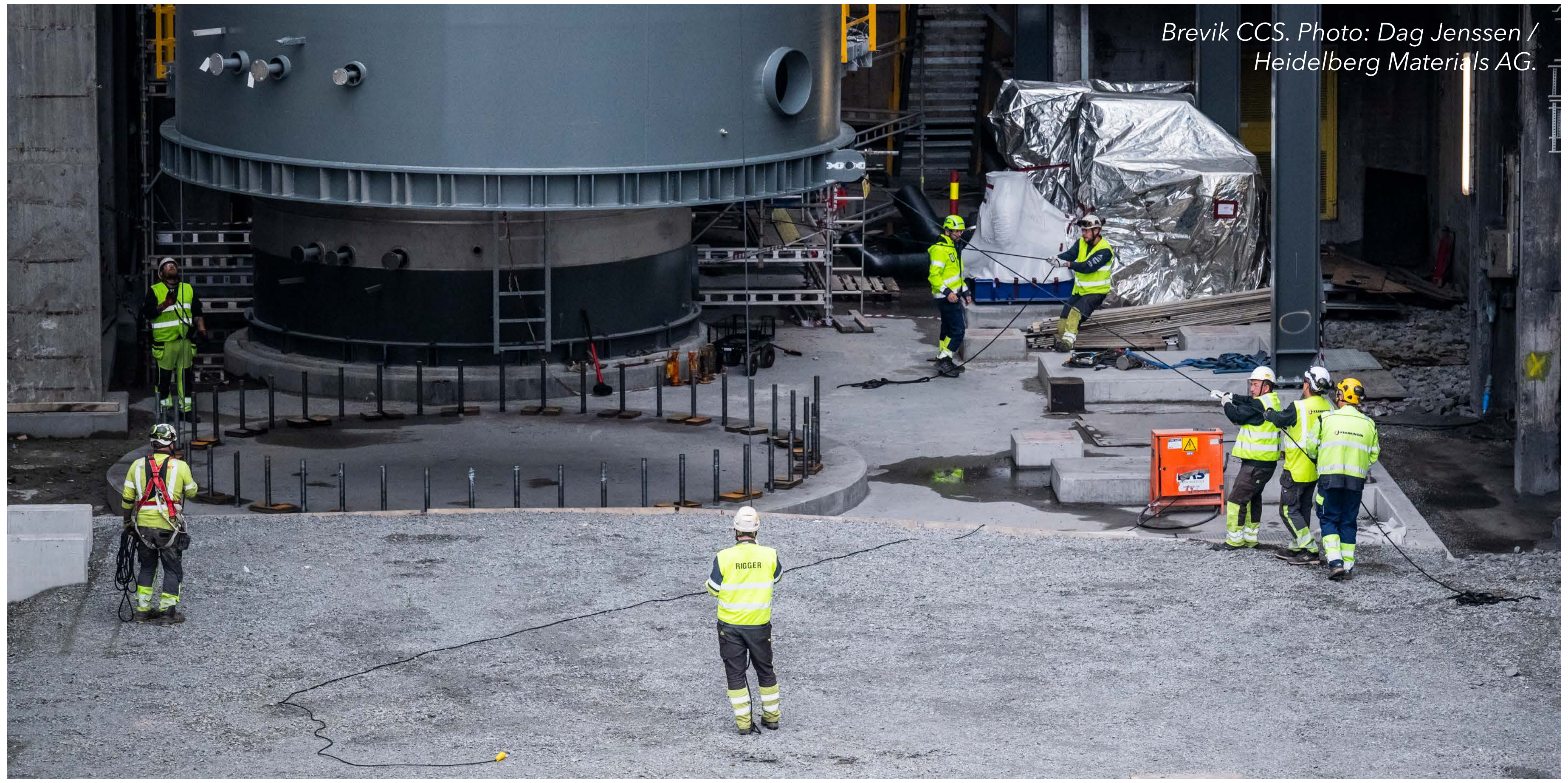


3 KEY CONSIDERATIONS

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.

©PorthosCO2

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%.

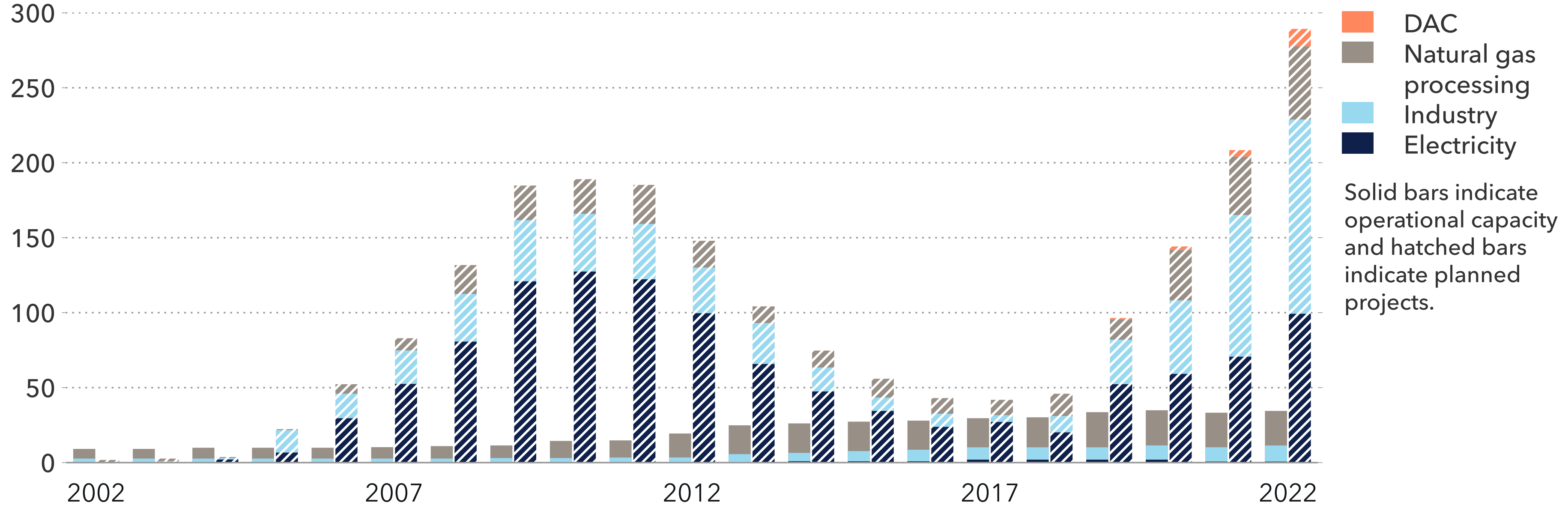
We found that the communication around carbon captured, capacity, and capture rates can be unclear, and the three terms are often used interchangeably. The deep-dive into each project has addressed these issues to give accurate capacities.

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

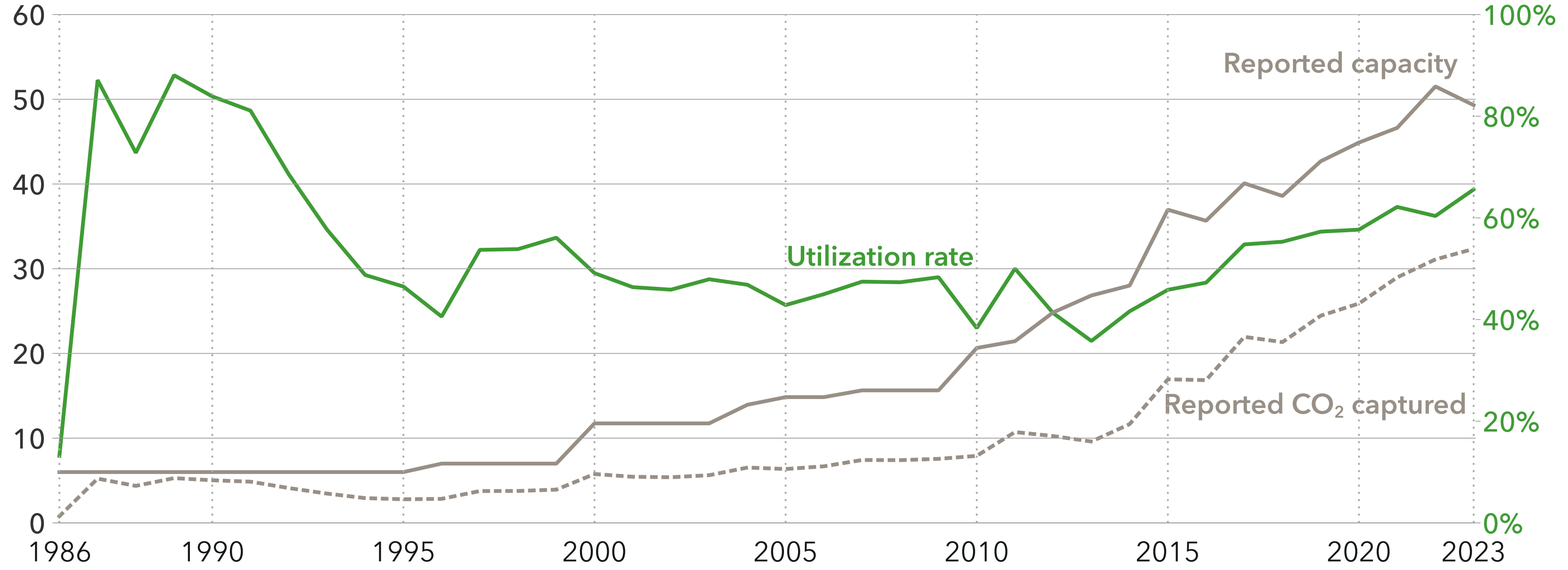


Note: Reproduced from Kazlou et al (2024) with permission from the authors.

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

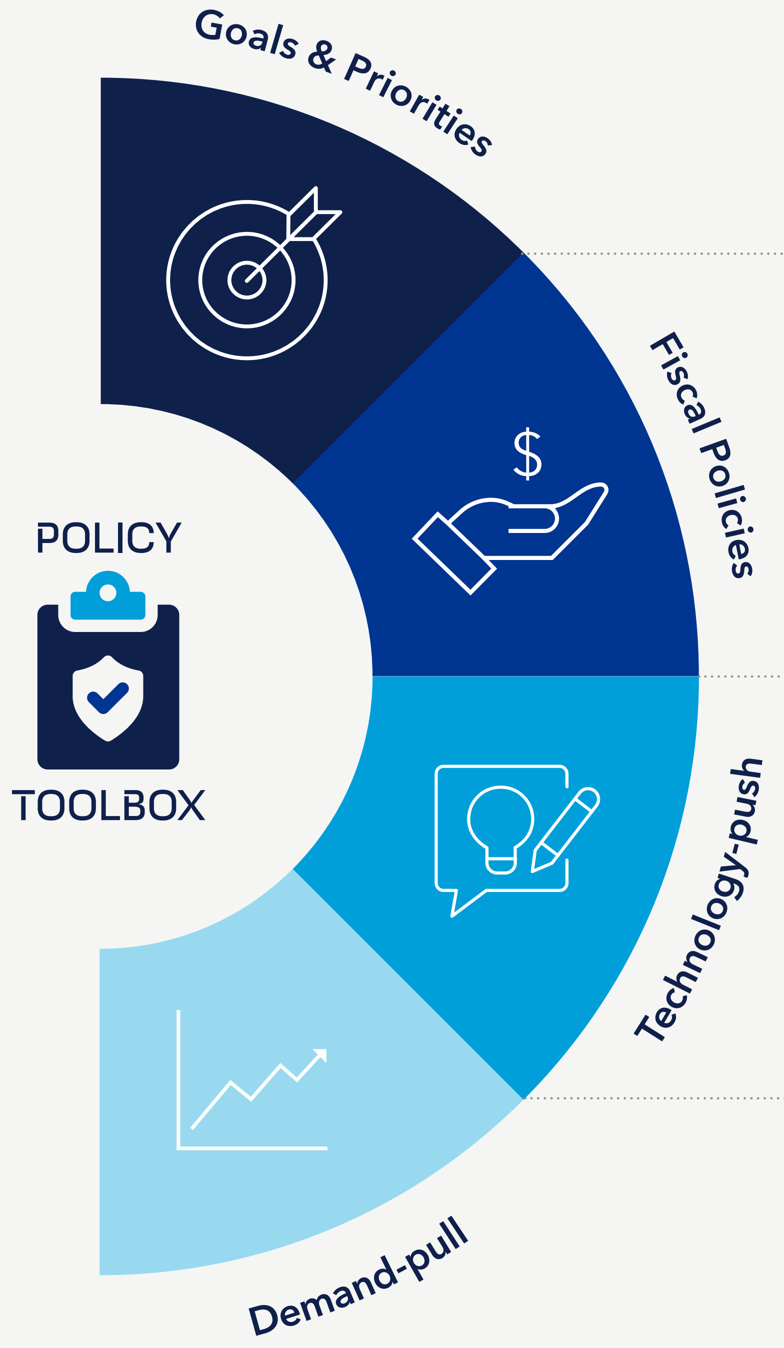
Public concerns about CCS projects include pipeline and storage safety, property value impacts, and broader environmental views on CCS as a viable solution. These issues, detailed in Section 4.2, affect project permitting and value chain setup. Building public trust and demonstrating societal and community 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)

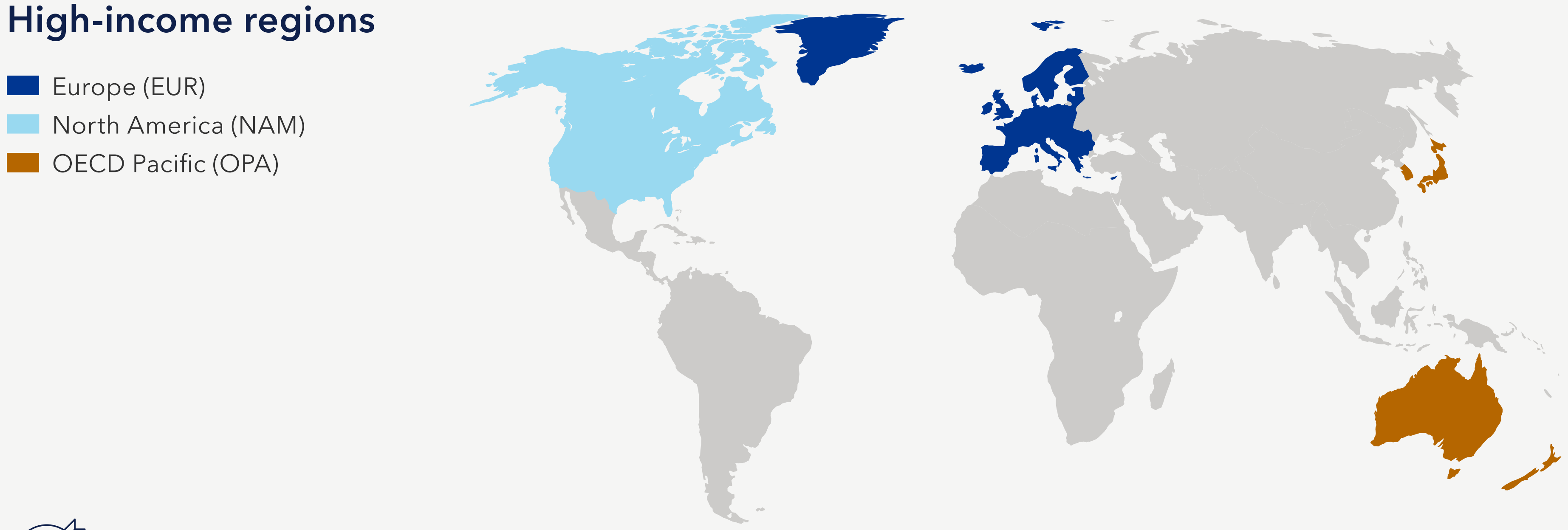
Purpose: Stimulate demand and incentivize market uptake
- **Mandates** for emissions reduction (e.g. use of low-carbon energy, CCS and storage deployment, public procurement of low-emission goods like cement and steel)
- **Funding** for investments, capital expenditure (e.g. equipment, conversions)
-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



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.

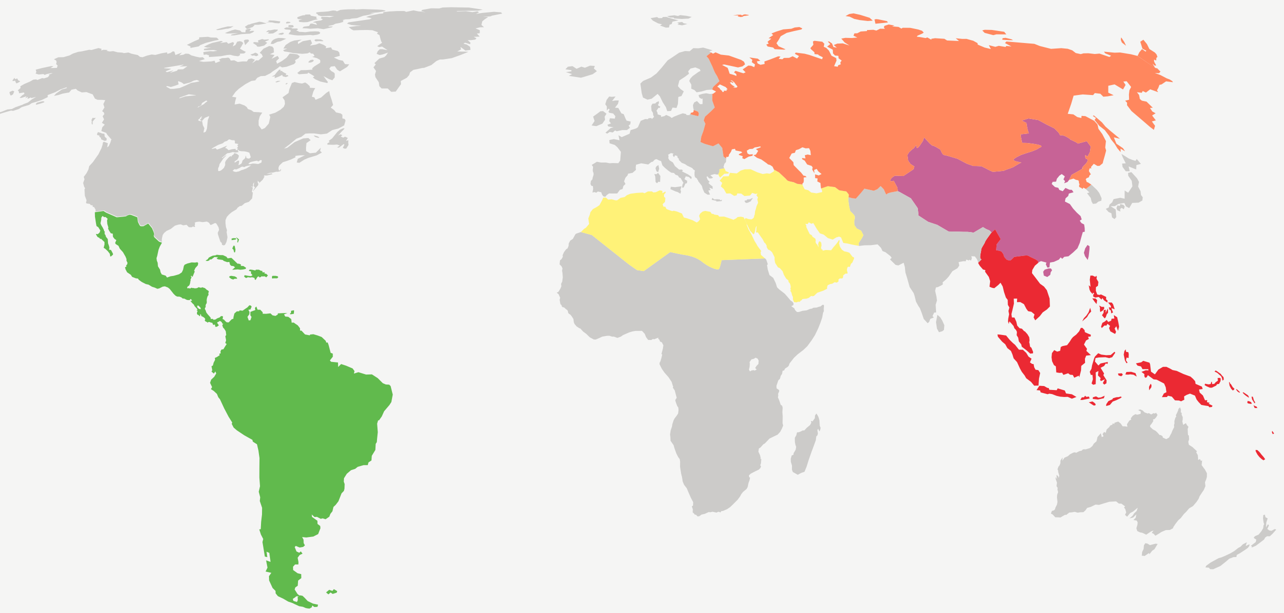
- **EUR:** We expect broader adoption of OPEX payments through carbon contracts for difference (CCfD) beyond country pioneers like the Netherlands and the UK following *Draghi* report recommendations (EC, 2024b). CCfD set a strike price and provide a hedging component against volatile EU ETS prices thereby 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

- Latin America (LAM)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- South East Asia (SEA)



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.

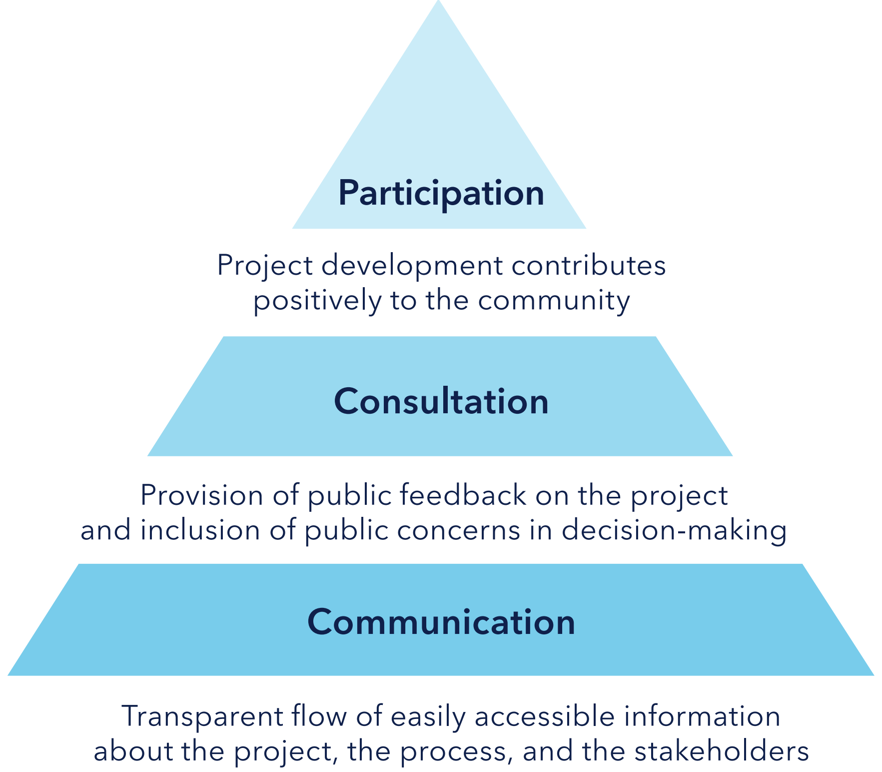
In 2021, the Heartland Greenway 2,000 km pipeline project was set to span five states in the US Midwest. The project planned to transport up to 15 $MtCO_2$/yr, captured from ethanol plants, for underground storage in Illinois. Local communities expressed strong resistance, citing concerns over land rights 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.

4.3 BUSINESS MODELS AND FINANCING

Cost of capital for carbon capture and storage

The cost of capital for investments in CCS, like any other investment, is determined by perceived risk. Our assumptions for the cost of capital are high and range from 10.5% to 16% in 2025 depending on the region, build out of CCS infrastructure, and policy support mechanism. In addition to typical risk drivers like market and regulatory factors, CCS faces a number of unique risks that influence the cost of capital.

Although elements of a typical CCS value chain are well developed (capture technologies, pipeline transport, and geological storage) CCS is not yet fully commercially mature in terms of widespread deployment. Capture projects in some industries can be first of a kind or can be one of few globally. Similarly, there are a number of emerging approaches to CO_2 transport and storage that have yet to be widely deployed.

The political context of any CCS development can alleviate or exacerbate risks. Direct subsidies targeted at any part of or the whole value chain will improve the cash flow picture for developers, while one-time state grants defray upfront costs. Access to cheap capital through national or municipal banks may also lower the risk of further investment for private lenders. Additionally, clear and specific regulation across the CCS value chain is key to efficient development and operation. Together, clear regulation and state support both grease the wheels of market efficiency by reducing barriers to entry and ensure efficient allocation of resources across the value chain.

The different parts of the CCS value chain do not operate in isolation and are subject to interdependencies that create cross-chain risks. Should one element of the value chain be impacted, all areas will be affected. For example, uncertainties around permitting a geological storage site in Denmark may prevent a capture facility in Germany from taking a final investment decision (FID), as the captured carbon has nowhere to go. All stages of the value chain need to develop for one part of the value chain to succeed. This issue highlights the importance of intergovernmental coordination and planning to ensure timely deployment of CCS.

CCS also presents an interdependency risk tied to future emissions in hard-to-decarbonize industries. CCS is a mitigation technology, meaning it will be deployed so long as carbon emissions need to be captured and it is financially reasonable to do so. The uptake of more efficient technology, altered processes, or lower utilization of the equipment all pose uncertainty to the economic lifetime and expected utilization rate of the CCS investment.

Another risk stems from the fact that CO_2 will need to be stored in perpetuity to be an effective climate mitigation measure. This creates a long-term storage liability and costs for monitoring the CO_2 in the subsurface. Typically, these long-term risks will sit with governments. For example, the EU *CCS Guidance Document 4* (2024) explains that a storage site should be owned and monitored by developers for at least 20 years post closure, after which the long-term responsibilities are typically transferred to governments. For this 20-year period, the developer has no income but incurs monitoring costs and costs towards financial securities in the case of leakage. This needs to be priced in when analysing the CCS business case. The financial costs for providing such long-term security can be lowered if national regulators allow for instruments other than cash deposits which are the most secure, but also most expensive option for CCS developers. Good alternatives are parent company guarantees or, if available, insurance products.

Regional variations

Across the regions, we observe two different styles of market, vertically or horizontally integrated markets, which have different implications for risks.

In vertically integrated markets, the rate of technology deployment is centrally determined by organizations, typically governments or SOEs, as in China and the Middle East. The advantage of this approach is speed of deployment, as governments can offer highly competitive rates on capital and coordinate project development across the value chain. However, vertically integrated markets may suffer from inefficiencies and highly concentrated risk, as rushed deployment results in poorly allocated risks and capital and quickly outdated technology.

Conversely, in horizontally integrated markets, the rate of technology deployment is primarily determined by market forces, typically private institutions, as in Europe and the US. The advantage of this approach is increased competition that leads to technological improvements, more efficiently allocated capital, and more diversified risk. The disadvantage of horizontally integrated markets is slower technology

CCS is a mitigation technology, meaning it will be deployed so long as carbon emissions need to be captured and it is financially reasonable to do so.

deployment; less centralized organization and direct support can result in higher exposure of participants to cross-chain risk.

Today, Europe and the US lead the world in terms of CCS projects in the development pipeline. Europe is moving projects forward amidst tightening emissions regulations and developers are are advancing in the US, taking advantage of the established 45Q tax credit. In that sense, the regions offer different policy mechanisms, where Europe offers a 'carrot and stick' while the US has resisted a national carbon pricing policy and focuses on the 'carrot' only.

The US

The country's long history of capturing and using CO_2 for EOR has contributed to a robust CCS knowledge base.

The Biden-era support schemes have generated significant growth in the CCS project pipeline in the US. In November 2021, the Biden administration passed the IIJA, followed by the IRA in August 2022. The IRA expanded the pre-existing 45Q tax credit (which was enacted in 2008 and enhanced in 2018), granting CCS facilities USD 85/tCO_2 for permanent carbon storage, USD 180/tCO_2 for DAC solutions with permanent storage, and USD 60/tCO_2 used in EOR or other forms of utilization (Carbon Capture Coalition, 2022).

Although the current administration's overhaul of clean energy funding programmes (with the Department of Energy) cast a shadow of uncertainty over CCS support, we expect that the 45Q tax credit is likely to remain largely unchanged.

From an investment perspective, the tax credits, subtractable from corporate income taxes, are effectively a subsidy that boosts the business case. They are tradeable and create certainty around a project's revenue potential, as is the case in the CCfD approach that is predominant in Europe.

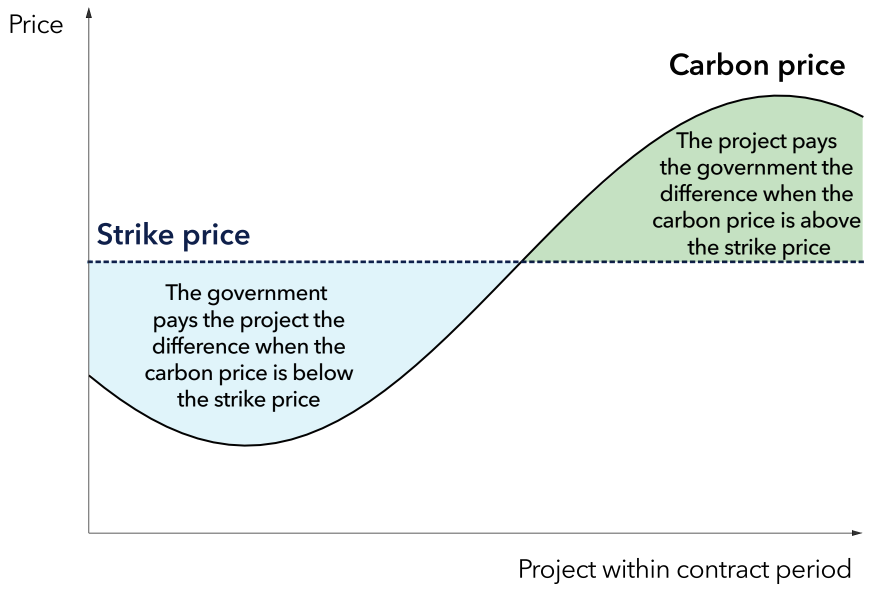
Europe

Europe paints a different picture for financiers of CCS value chains. Today, at current EU ETS levels, some form of government support is needed to enable deployment. This is evident when looking at recent FIDs for CCS projects.

The Norwegian government pioneered Europe's first full-scale value chain for CO_2 management, Longship (Northern Lights), providing USD 2bn in support across capture, transport, and storage. Covering around two-thirds of total costs, the project represents the largest sum Norwegian authorities have ever invested in a single climate project (Norwegian Ministry of Energy, 2024).

The UK, Netherlands, Denmark, and France all opted for a different funding mechanism using CCfD that guarantee the difference between a project's strike price (carbon avoidance cost) and the variable carbon market price. If the actual carbon price is higher than the strike price, the situation is reversed (see the figure on this page). This offers stable, long-term cashflow to developers where the cost to society depends on the actual development of the EU ETS or the UK ETS. With carbon prices expected to rise, the subsidy needs will reduce over time and cease after the contract period, typically 10 to 15 years. Still, total costs for these schemes are significant: the UK government expects a cost of USD 29bn in relation to funding two CCS developments at Teesside and Merseyside Northern England.

Principle behind carbon contracts for difference



If we look at private capital flows into European CCS, the common denominator is that project owners are state-owned entities or oil majors (Netherlands Court of Audit, 2024). For example, the Dutch Porthos project is being developed by the Port of Rotterdam, Gasunie, and state energy company EBN, all of which are partly state owned. Also the largest Dutch CCS development, called Aramis, saw a recent increased exposure to state ownership, after Shell and TotalEnergies decided to not invest in the construction of the pipeline transport infrastructure. The Dutch government therefore took over this role and increased ownership by injecting USD 726m in new equity.

The industry reached a commercial milestone with the recent FID for phase two of Norway's Northern Lights: private capital started to flow into the project to realize the expansion. After the USD 2bn invested by the Norwegian government, USD 600m has come from Equinor, Shell, and TotalEnergies, with an additional USD 150m from EU funding (Equinor, 2025). This demonstrates the real value of scalable, full value chain developments which can be developed in phases and where the need for government funding can be adjusted downwards over time. The trick is phasing investment needs while still providing an end-solution that offers economies of scale.

The positive momentum in Europe – with recent investment decisions for Dutch Porthos, Norwegian Northern Lights, Danish Greensand, and British Teesside – is clearly driven by a great deal of government subsidies. With government treasuries under pressure to increase spending on areas other than climate, the success of European CCS will be largely determined by the successful commercialization of these projects. State-owned developers and oil companies will need to work together to reduce risks by quickly applying learnings and embracing the opportunity to drive the costs down for future expansions. If market expectations of rising European carbon prices are realized, the business case for CCS on market terms will strengthen, eventually accelerating deployment.

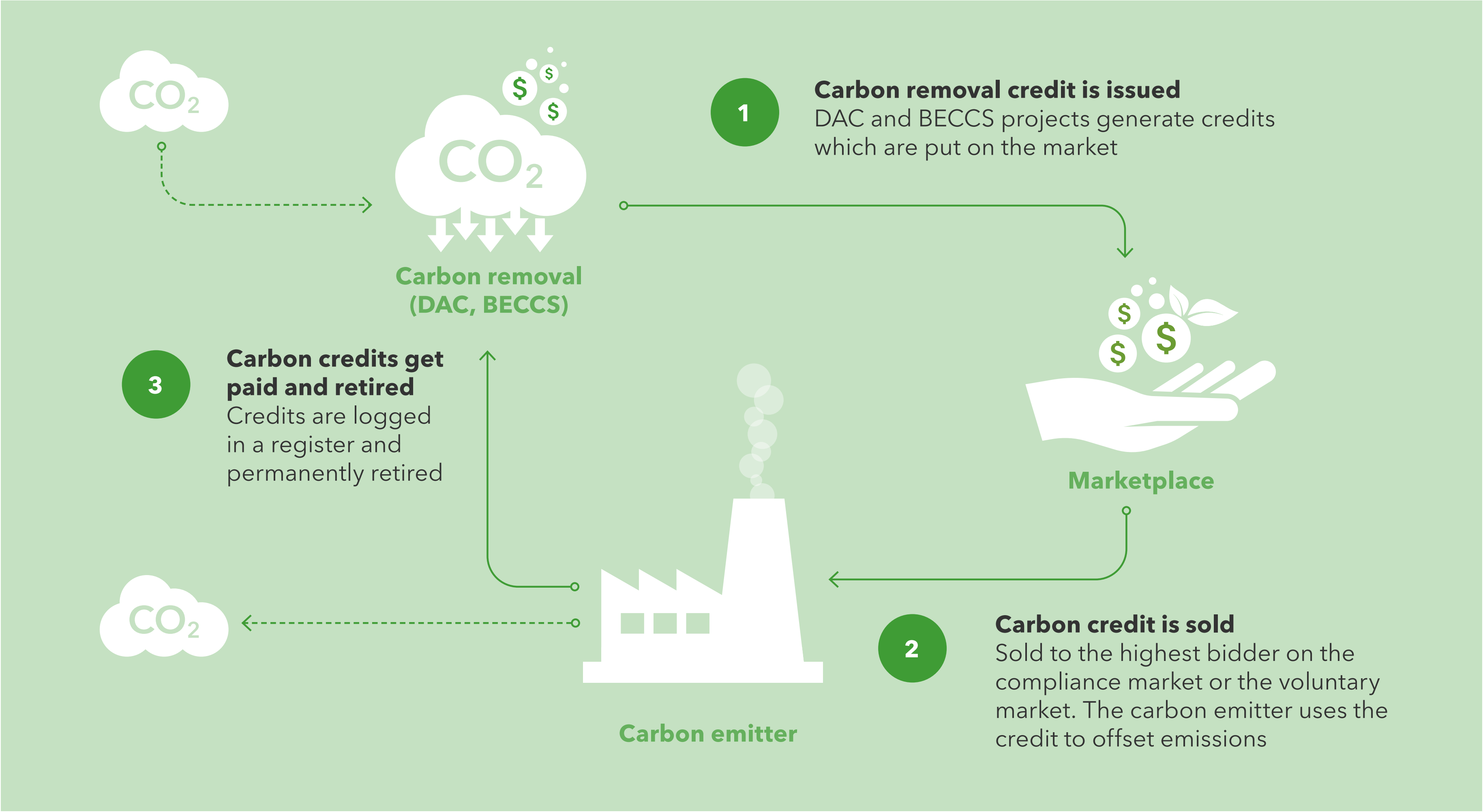
4.4 HOW CARBON MARKETS DRIVE CARBON DIOXIDE REMOVAL

The demand for CDR technologies, like BECCS and DAC, is driven largely by carbon markets. These solutions, when paired with CO_2 storage, achieve negative emissions by removing CO_2 from the atmosphere and are therefore used to generate carbon credits. Carbon credits can also be generated through nature-based solutions that utilize ecosystems for carbon capture and storage, such as reforestation or soil carbon sequestration, but these are not included in this forecast. CDR is not a substitute for emission reduction, but will be required to offset emissions from sources that cannot otherwise be decarbonized, and thereby to achieve net zero. The longer we wait to reduce emissions, the more important CDR will become. As global demand for carbon credits has increased, there has been strong growth in both funding for and attention to technology-based solutions such as DAC and BECCS. According to Global Market Insights, the current market value of the voluntary carbon market is USD 1.7bn (GMI, 2025). We expect the market to grow to USD 15.7bn in 2034 and the share of technology-based CDR to increase.

CDR projects generate carbon credits that can be used either as a compliance tool or to meet voluntary reduction commitments by companies and consumers. CDR projects must be validated and verified according to an accepted standard. These standards can be from a non-governmental organization, such as Verra or Puro.earth, or from a regulatory body such as the EU Carbon Dioxide Removal Certification Framework, which is currently in development. The verification process ensures that the amount of CO_2 removed and stored is accurately quantified, with safeguards in place to ensure projects are truly additional (i.e. the project has resulted in carbon removals above and beyond what would have occurred without the project existing) and sustainable.

There are two primary markets for carbon credits: compliance markets and voluntary markets. Verified carbon credits can also be sold business-to-business, which occurs outside of formal carbon markets. Compliance markets are regulated by mandatory national, regional, or international carbon reduction regimes and are usually aimed at energy-intensive emitters such as iron and steel producers, oil refineries, power generators, airlines, and processing companies. Voluntary markets function outside of compliance markets and therefore do not currently involve any direct government or regulatory oversight. However, the distinction between the voluntary and compliance markets is becoming less strict. Some countries (e.g. South Africa and Colombia) and sectors (e.g. the CORSIA scheme for international civil aviation) allow certain voluntary market credits to be used for compliance (Tamme, 2023).

Voluntary markets allow businesses and individuals to purchase carbon credits to offset their own emissions. Companies can voluntarily set their own GHG emission targets to demonstrate a commitment to



environmental responsibility. To show compliance, companies have their GHG bookkeeping verified according to generally accepted standards (accounting rules). Purchased credits are logged in a register and permanently retired. The organization responsible for the standard to assure the GHG avoidance or removal will keep this register.

Within voluntary and compliance markets, there is also a primary market and a secondary market. The primary market is where credits are created by a project and then transferred to the first buyer and/or issued into a register. The secondary market is where credits or allowances that have already been issued and logged in a register are transferred from one account to another. As with other markets, carbon credit trades can be made bilaterally or through an exchange. Examples of carbon credit exchanges are the Expansive CBL (New York) and the AirCarbon Exchange (Singapore). These exchanges create standard products to simplify and speed-up transactions, allowing for lower transaction costs. The exchanges generally only operate in the secondary market and not the primary market.

4.5 REGULATIONS AND LEGAL ISSUES

DNV's forecast for CCS deployment presented in Chapter 5 assumes the necessary laws and regulations have been established. This is not currently the case in all jurisdictions where CCS projects are emerging. The absence of the necessary legal and regulatory frameworks will typically delay, or even prevent, deployment when left unaddressed. There are a variety of intricate legal and regulatory matters that must be considered in each part of the value chain.

Governments must establish regulations governing the subsurface storage of CO_2, typically in alignment with land laws. These regulatory frameworks help to clearly delineate the responsibilities and liabilities of the parties involved in CO_2 storage and foster public trust by ensuring that storage projects adhere to stringent oversight and safety standards. Typically, a competent authority will be established to govern the legal basis for CO_2 storage and to manage the associated permitting process.

Defining responsibility for the CO_2 throughout the lifecycle of a store is an important requirement of such regulation. CO_2 will be stored underground in perpetuity, creating various liabilities such as potential leakage or environmental impacts. Regulations will often define a period after closure when selected liabilities are transferred from the operator to the government.

CO_2 pipeline regulations aim to ensure the safe and efficient transport of CO_2 that minimizes risks to people and the environment. Such infrastructure is subject to strict requirements that typically address design and installation, operational and maintenance guidelines, strict reporting requirements including regular inspections, emergency response mandates, public communication protocols, and detailed safety analysis.

Air permitting requirements for carbon capture plants ensure compliance with air quality standards, minimizing the release of pollutants during the capture process. Permitting processes typically involve assessing emissions including CO_2, NO_X, SO_X, and particulate matter. Such air permits are crucial to maintain air quality standards and support environmental protection and public health as industrial carbon capture technologies are increasingly deployed.

Is progress being made?
Regions that are considered mature in terms of CCS deployment have well-defined regulations addressing the full CCS value chain.

In the US, for example, the EPA's *Underground Injection Control Program* (EPA, 2025) regulates CO_2 injection for geological storage. It classifies CO_2 injection wells as Class VI, designed for long-term storage in deep rock formations. The Program enforces strict site characterization, well construction, and operational standards to prevent CO_2 migration into drinking water sources. It also requires continuous monitoring, financial responsibility demonstrations, and detailed closure and post-closure care plans. These requirements aim to safeguard groundwater and support safe CCS technology deployment.

The EU's *CCS Directive* (EU, 2009) establishes a comprehensive legal framework for the environmentally safe geological storage of CO_2. It outlines the responsibilities and liabilities of different parties involved in CCS projects, ensuring rigorous oversight and safety standards. Furthermore, it interacts with the EU ETS and provides the mechanism whereby captured emissions can be deducted from obligations. The *CCS Directive* is transposed into national law by member states. Guidance documents have been established to help with the interpretation of the associated legal text (EC, 2024c).

Conversely, countries in the earlier stages of CCS deployment will often have regulatory gaps which can be challenging and time consuming to address.

International cooperation to enable greater deployment
The cross-border transportation of CO_2 enables regions that lack storage options to still pursue capture projects. However, the absence of comprehensive and harmonized regulatory frameworks across jurisdictions, such as the EU ETS, can add complexity. Eliminating regulatory barriers to cross-border CO_2 transport can help to accelerate regional CCS deployment.

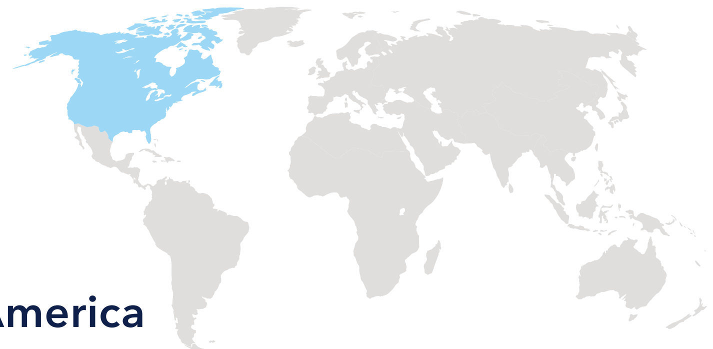
One important international agreement for cross-border CO_2 transport is the *London Protocol* (IMO, 2006). Administered by the International Maritime Organization (IMO), the main goal of the Protocol is to keep the seas clean by stopping pollution from waste dumped in the ocean. Currently, CO_2 is characterized as 'waste' under the Protocol, which has implications for offshore CO_2 storage where countries involved are signatories.

Recognizing the potential for CCS to mitigate climate change, the Protocol was amended in 2006 to allow the storage of CO_2 offshore. However, restrictions remain regarding the export of CO_2 for offshore storage. An amendment to allow export of CO_2 for offshore storage has yet to enter into force because it lacks the necessary ratification from two-thirds of the parties. Diplomatic efforts to secure the required ratification are ongoing, and an interim solution has been adopted. This allows for export where a country declares provisional application of the amendment and suitable bilateral agreements are lodged with the IMO.

A wide variety of bilateral and multilateral government initiatives (IEAGHG, 2025; CSL Forum, 2025; Clean Energy Ministerial, 2025) have been established. Many of these collaborate on legal and regulatory matters. We expect such efforts to become increasingly important for addressing gaps in regulatory frameworks in less mature countries and enabling wider deployment of CCS value chains across international borders.

4.6 CURRENT STATUS BY REGION

The following section summarizes activities in key regions where CCS is being deployed.



North America

North America is the leading region globally in CCS deployment. This is driven primarily by the storage of CO_2 through EOR and, in recent years, by the flagship 45Q policy. CCS and related technologies such as DAC, low-carbon hydrogen (fossil-based production with CCS), and ammonia production have made significant advancements in the region.

The policy landscape for CCS has seen significant developments in both the US and Canada in recent years. In 2022, the US Department of Energy announced an expansion of the existing 45Q tax credit (see Section 4.1) under the IRA, decreasing capture thresholds to make it more accessible, increasing credit value, and extending the commence construction window. This has contributed to a significant increase in the project pipeline. Additionally, the US has introduced funding support for CCS and DAC projects and new incentives for low-carbon hydrogen production. Despite current uncertainty around how US energy policy will evolve, the 45Q tax credit is widely expected to remain in place.

In Canada, major changes took place in 2024 when the federal government updated its *Clean Fuel Regulations* to incorporate stronger incentives for CCS. Alberta and Saskatchewan introduced new policies to fast-track project approvals, addressing concerns over regulatory delays. However, interprovincial coordination remains a challenge, particularly where infrastructure crosses multiple jurisdictions.

A number of major corporations in the US have ramped up investment in low-carbon technologies to support climate commitments, particularly within the tech sector. Microsoft and Google have announced strategic partnerships with energy providers to integrate CCS into their data centre operations with the aim of mitigating the carbon impact of growing AI-driven electricity demand. In parallel, such companies are making significant investments in CDR technology, with Microsoft being the world's leading purchaser of durable CDR.

One of the largest coordinated CCS efforts in the region is the Pathways Alliance in Alberta, Canada. The USD 16.5bn project, which will transport CO_2 from oil sands operations, has secured additional funding from the federal government and private

Boundary Dam Power Station in Saskatchewan. In 2014, it became the first power station in the world to successfully use CCS technology.

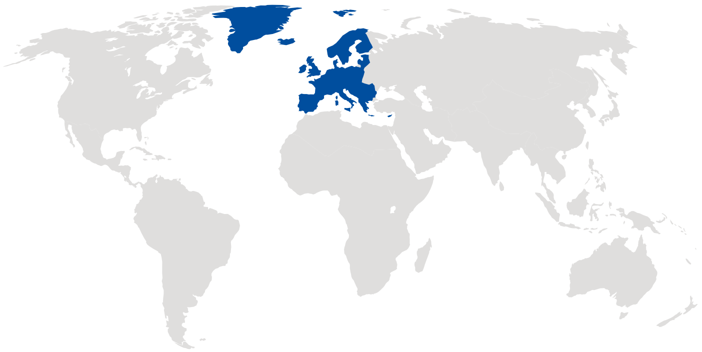
investors. The project is on track to begin operation in 2027 and signals growing confidence in long-term carbon transport and storage solutions.

The US Department of Energy's USD 3.5bn commitment to DAC hubs has resulted in multiple large-scale projects emerging. One of the most notable US DAC projects is 1PointFive's Stratos DAC facility in Texas, which is expected to begin operations in 2025 and will scale to remove 500,000 tCO_2/year. In 2024, the Canadian government announced additional funding to accelerate DAC deployment, aligning with international carbon removal targets.

Both the low-carbon hydrogen and ammonia markets have experienced accelerated growth in North America, fuelled by policy support and global demand. Air Products has announced an expansion of its low-carbon hydrogen facility in Louisiana, increasing capacity by 40%. Meanwhile, blue ammonia has emerged as a major export opportunity. Japan and South Korea have increased their commitments to ammonia-based power generation, leading to a surge in North American export activity. We expect the expansion of dedicated export terminals along the Gulf Coast and in British Columbia to further facilitate such trade.

In the US, developers continue to face prolonged approval timelines for CO_2 pipelines and storage sites. Efforts to streamline permitting, including recent policy adjustments, have improved but not fully resolved this issue. Public opposition to CO_2 pipelines remains a challenge, with community concerns over safety and land use impacting project timelines.

The Petra Nova facility that captures CO_2 from post-combustion flue gas at NRG's W.A. Parish coal power plant in Texas, USA. Image courtesy of Petra Nova facility owner, ENEOS Xplora Inc.



Europe

Europe is another leading region for CCS deployment, also as a result of strong policy support. The EU has established a legally binding target to be climate neutral by 2050 and sees the deployment of CCS, particularly in hard-to-decarbonize sectors, as a key tool to achieve this. The EU's industrial carbon management strategy, adopted in February 2024, established targets to capture 450 MtCO_2/yr by 2050. Moreover, the *Net Zero Industry Act* mandates oil and gas producers to collectively invest in, and provide, storage capacity of 50 MtCO_2/yr by 2030.

CCS development in Europe to date is largely driven by two things: the financial incentive to reduce EU ETS obligations and the provision of subsidies. The cost of meeting obligations by purchasing allowances on the EU ETS is the main incentive for emitters to capture CO_2. We expect the value of EU allowances to increase: our forecast anticipates a carbon price in Europe of USD 150/tCO_2 (EUR 140/tCO_2) in 2030 and USD 220/tCO_2 (EUR 200/tCO_2) in 2040. Where North America has focused on tax credits to enable CCS projects, direct funding is more prominent in Europe. At the EU level, the Innovation Fund, the Connecting Europe Facility for Energy – available to cross-border infrastructure PCIs – and Horizon Europe have been three key support mechanisms enabling CCS deployment. At the country level, there are various direct funding, grant, and CfD schemes addressing the difference between the cost of CCS and the EU ETS, which can help to strengthen the business case for CCS projects.

Europe's commitment to CCS has strong momentum; more than 100 commercial-scale CCS projects are currently in development. Regional development is characterized by CCS clusters, where CO_2 transport and storage is managed and offered as a service to emitters. Developers from the oil and gas industry are the main drivers of large-scale storage projects. This approach leverages economies of scale, with shared infrastructure consolidating larger volumes and emitters paying a tariff for CO_2 transport and storage. Various bilateral and multilateral agreements are in place to enable cross-border transport and storage of CO_2 in proximate countries such as Denmark, the Netherlands, and Norway. We expect such agreements to become increasingly important as emitters in countries that currently lack local storage, such as Germany, begin to use CCS to decarbonize.

The North Sea is currently the dominant location for CO_2 storage sites in Europe, but storage projects are emerging elsewhere, including in Greece, Italy, and Poland. Denmark is the first country in Europe that has awarded multiple exploration licenses for CO_2 storage onshore. This development could be important for future CCS deployment in Europe, as it offers the potential for cost reductions compared to offshore storage (see Section 2.4).

Europe is also home to the pioneering Sleipner project in Norway. Operating since 1996, this was the first CCS project to store CO_2 purely geologically (i.e. not for CO_2 EOR). In 2025, the continent's first cross-border open-source CO_2 transport and storage facility is set to commence operations. Northern Lights, based in Norway and part of the Longship project, is the world's first CCS project to transport CO_2 by ship. The first capture plant to deliver CO_2 to the facility will be the Heidelberg Materials Brevik cement plant in Norway, followed by Yara Sluiskil in the Netherlands, and Ørsted's two heat and power plants in Denmark. Northern Lights was built with expansion in mind and took its FID for phase two in March 2025.

Significant progress is also being made elsewhere in Europe. Greensand Future in Denmark took FID in 2024 and is expected to be operational by early 2026. In the Netherlands, Porthos started construction in 2024 and is expected to be operational by 2026. Aramis, another large-scale Dutch project is currently in advanced development.

Interest in CDR projects, particularly BECCS, is growing in Europe. Sweden and Denmark have launched specific subsidy schemes that target negative emissions, and many projects have sought to sell credits in the voluntary carbon market. These include Ørsted's bioenergy thermal power plants, Hafslund Oslo Celsio's waste-to-energy plant, and Stockholm Exergi's biomass power plant. The regulatory landscape around CDR is evolving in parallel, with the EU's Carbon Removal Certification Framework establishing certifications for high-quality carbon removals and facilitating further investment.

The UK's CCS ambition is to capture and store 20 to 30 $MtCO_2$/yr by 2030. The UK also wants at least 5 $MtCO_2$/yr of CDR by 2030.

The UK has committed to deploy CCS in at least two industrial clusters: FID was taken for the Track1 East Coast Cluster in December 2024 and Hynet North West in April 2025. The Track 2 Transport and Storage solutions, Viking and Acorn, are in development awaiting clarity on government support.

Interest in CDR projects, particularly BECCS, is growing in Europe.

The Heidelberg Materials cement plant in Brevik, Norway. Photo: Heidelberg Materials AG.

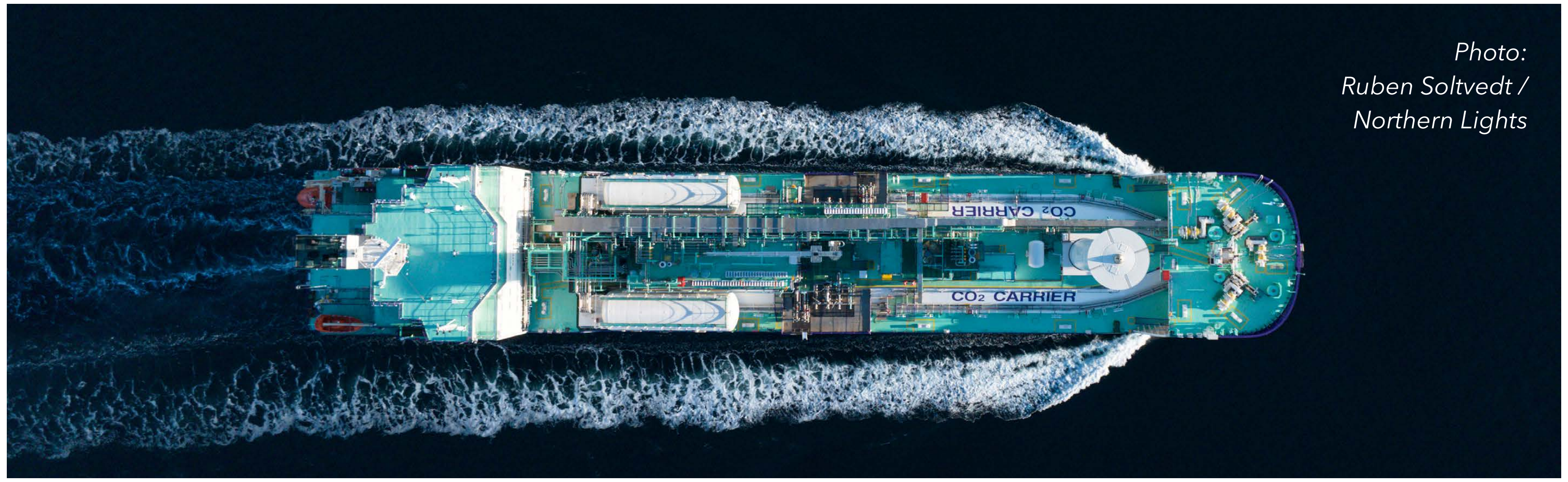
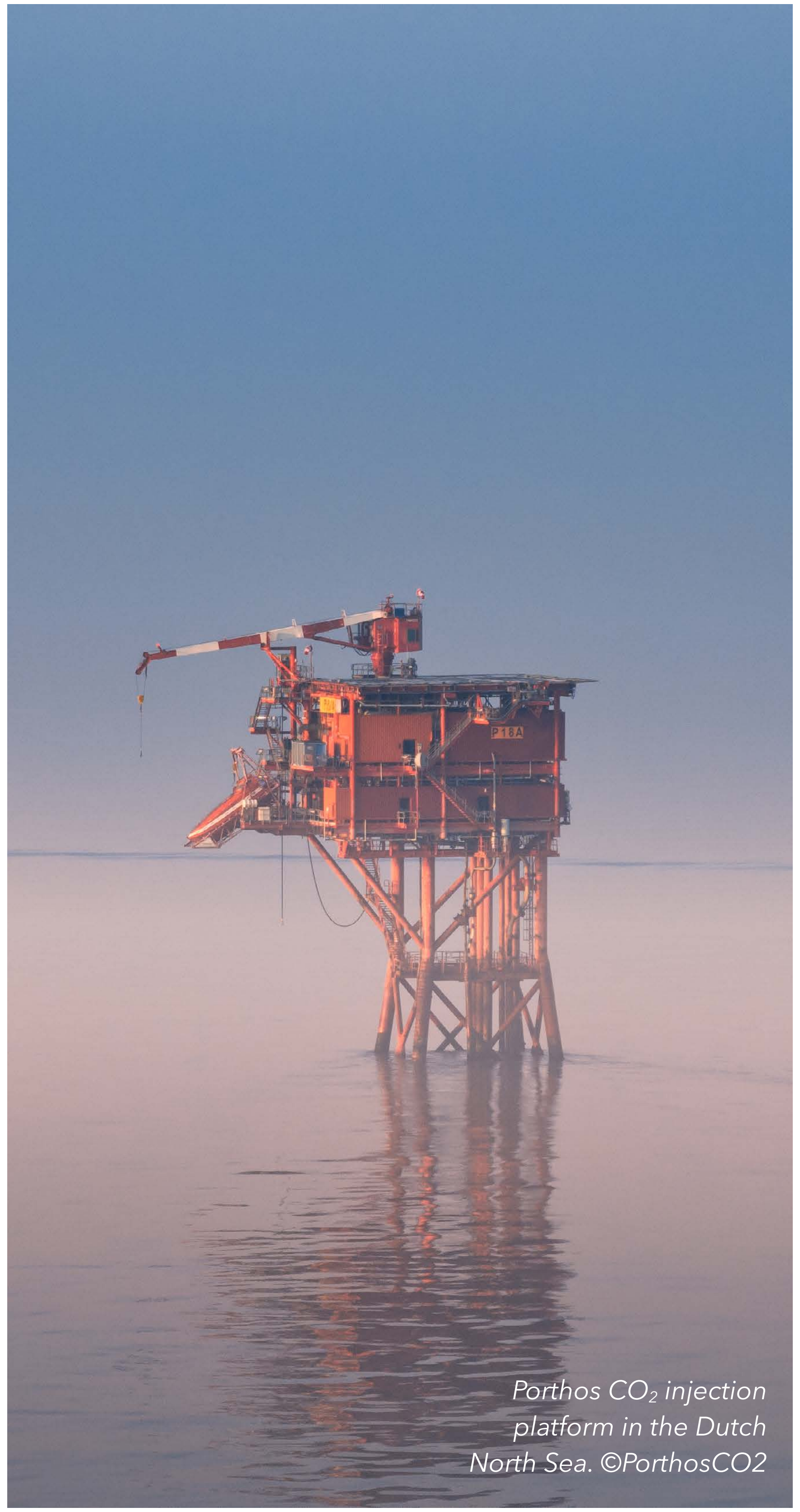


Photo: Ruben Soltvedt / Northern Lights

Sleipner, Norway. Photo: Øyvind Gravås and Bo B. Randulff ©Equinor.



Porthos CO_2 injection platform in the Dutch North Sea. ©PorthosCO2

Middle East and North Africa

The region has significant CCS ambition, with three operational CCS projects and six under construction. Operating facilities include the Al Reyadah steel plant in the UAE, Qatar's Ras Laffan LNG Facility, and Saudi Arabia's Uthmaniyah gas processing plant. The world's largest CO_2 utilization facility, United Jubail Petrochemical, is also in Saudi Arabia. The facility converts 0.5 $MtCO_2$/yr into feedstock for chemical processes. Initially driven by EOR, the regional CCS focus is increasingly changing to decarbonizing energy and the production of low-carbon fuels.

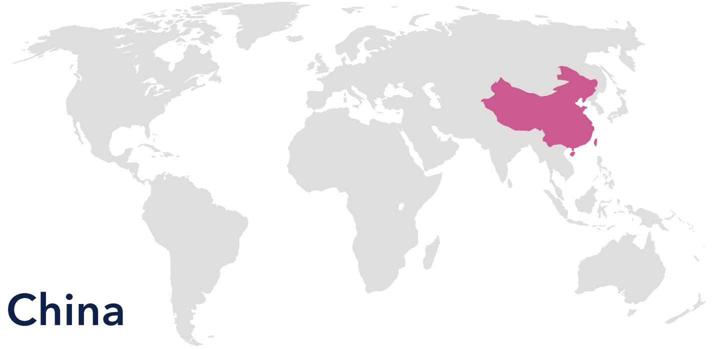
The UAE's *Long Term Strategy* highlights CCS as crucial for industrial sector decarbonization, targeting 43.5 $MtCO_2$/yr capacity by 2050. ADNOC plans a USD 23bn budget for decarbonization, aiming for 10 $MtCO_2$/yr captured by 2030 and net-zero operations by 2045. ADNOC's Habshan and Ghasha Concession projects, each with capacity of 1.5 $MtCO_2$/yr, are currently under construction.

Saudi Arabia aims to capture and store 44 $MtCO_2$/yr by 2035 and launched a domestic carbon crediting scheme in 2024. By 2027 the Jubail CCS hub in Saudi Arabia will store 9 $MtCO_2$/yr from natural gas processing and industrial sources in an onshore saline aquifer.

Oman aims to utilize its pipeline infrastructure for hydrogen and CO_2 transport in new CCS and EOR projects. DAC projects are emerging in Saudi Arabia, the UAE, and Oman, often combined with CO_2 mineralization or sustainable aviation fuel production.

Initially driven by EOR, the regional CCS focus is increasingly changing to decarbonizing energy and the production of low-carbon fuels.

Ras Laffan LNG Facility, Qatar

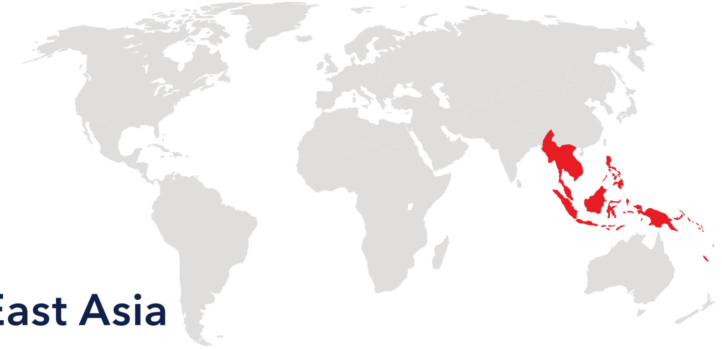


Greater China

China has established targets to achieve peak emissions by 2030 and carbon neutrality by 2060. CCS is seen as critical to achieving these targets and its deployment will continue to be supported as part of the *15th Five-Year Plan*. Financial mechanisms such as the People's Bank of China's Carbon Reduction Facility and Clean Coal Refinancing Loan have supported CCS deployment. With the expansion of China's national ETS to cover 60% of total emissions (see page 38), we expect carbon pricing to become a driving factor for CCS activity in future.

There are a number of operational CCS facilities in China including Sinopec's Qilu Petrochemical CCS facility, which captures 1 $MtCO_2$/yr. Several other CCS facilities are currently in construction, including the world's largest carbon capture project on a power station, a 1.5 $MtCO_2$/yr facility on the Huaneng Longdong Energy Base coal-fired plant.

PT Pertamina Balongan refinery in Indramayu, Indonesia

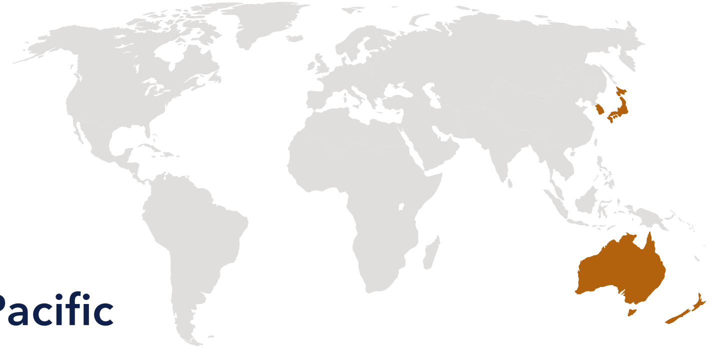


South East Asia

Several countries in South East Asia view CCS as key for sustainable development, as it provides opportunities for economic growth while reducing net greenhouse gas emissions. With various bilateral and multilateral agreements established, cross-border collaboration characterizes CCS deployment in the region. Malaysia and Indonesia are currently developing regional hubs to enable storage of CO_2 from both domestic sources and nearby countries such as Singapore, Japan, and Korea.

Policy and regulatory frameworks are being implemented to enable CCS. In Malaysia, the *Carbon Capture, Utilization, and Storage Act* (2025) and the *Land (Carbon Storage) Rules* (2022) in Sarawak have been introduced to regulate capture, transportation, and storage. The Malaysia Carbon Capture, Utilization, and Storage Agency oversees these activities, providing a detailed regulatory environment for cross-border CO_2 transport.

Indonesia's *Government Regulation No. 71 of 2019* and various specific CCS regulations establish a framework for cross-border CO_2 transportation. These regulations outline the rights, obligations, and liabilities of parties involved.



OECD Pacific

In Australia, several commercial-scale projects are operational including Chevron’s Gorgon CO_2 Injection Project in Western Australia and Santos’ Moomba project.

Japan has committed funding for nine CCS projects as part of its Long-Term CCS Roadmap, with four of these projects focusing on cross-border CO_2 transport and storage value chains.

Australia's *Environment Protection (Sea Dumping) Amendment Act* (2023) and provisional application of the 2009 *Amendment to Article 6 of the London Protocol* (see Section 4.5) allow for the import and export of CO_2 for offshore storage. State governments are also exploring CCS hubs and networks for potential cross-border CO_2 transport.

Several countries in the region are investing in DAC technologies. Japan and South Korea have introduced subsidies and grants to encourage the development and scaling of DAC. Similarly, the Commonwealth Scientific and Industrial Research Organization in Australia is supporting the development of several such technologies.

Latin America

In Latin America, Brazil is leading CCS deployment. In October 2024, Brazil enacted its first legal framework for CCS known as the ‘Fuels of the Future’ bill. This law aims to regulate CCS activities involving CO_2 capture, transportation, and geological storage. The National Agency of Petroleum, Gas, and Biofuels (ANP) will oversee operations, issue standards, and grant authorizations valid for 30 years. In areas with existing exploration contracts, ANP will consult rights holders before granting CCS authorization. EOR operations will be treated separately. CCS operators must address emergencies, maintain carbon storage records, and monitor CO_2 storage and leakage.

Existing CCS operations in Brazil are related to Petrobras’ EOR activities in the Santos Basin. Petrobras currently stores over 10 $MtCO_2$/yr and plans to increase that to 30 $MtCO_2$/yr by 2030.

Petrobras P-74 platform, which operates off the coast of Bacia de Santos, captures and reinjects CO_2. Photo: André Ribeiro / Agência Petrobras.

5 OUTLOOK

This chapter presents forecast results from our CCS deployment modeling. We present cost trajectories across the value chain for different sectors and regions, uptake by sector and by region, the outlook for carbon dioxide removal technologies, and our expectations of the overall impact of CCS on carbon emissions.

Greensand storage facility, Danish North Sea. Photo: INEOS Energy - Project Greensand

FORECAST HIGHLIGHTS

Our forecast for CCS uptake before 2030 is **based on known projects** with adjustments made to account for development status and project uncertainties. As a result, we forecast **270 $MtCO_2$/yr** of capture capacity in 2030, with 210 $MtCO_2$/yr expected to be captured and stored that year.

These projects are moving forward because there is strong support for CCS from governments. Approximately **two-thirds of the projected capacity additions will occur in North America and Europe**, with North America being the leader in total installed CCS capacity by the end of 2030.

Starting in 2030, CCS capacity will grow beyond known projects if the cost of CO_2 avoided is competitive with the carbon price, with regional policy support helping drive adoption in the early years. From the late 2030s onward, CCS deployment becomes mainly cost driven, influenced by falling technology costs and rising carbon prices. As a result, we **forecast 1.3 $GtCO_2$/yr to be captured and stored in 2050**.

Europe is set to catch up with – and eventually surpass – **North America** in its share of global CO_2 capture and storage, driven by higher carbon prices and a strong focus on industrial CCS. The **Middle East and North Africa** will contribute through low-carbon hydrogen, while **Greater China** will focus on coal power and steel production.

TO 2030: HYDROCARBON PRODUCTION DRIVES UPTAKE

AFTER 2030: HARD-TO-DECARBONIZE SECTORS TAKE OVER

AFTER 2040: CARBON REMOVAL STARTS TO SCALE

Most of the CCS deployment from known projects will be **driven by decarbonizing the hydrocarbon production sectors** (natural gas processing and low-carbon hydrogen and ammonia), where capturing carbon is generally cheaper due to higher CO_2 concentrations and existing infrastructure.

We expect policy-driven growth in CCS capacity to **lower costs by about 14% by 2030**, mainly due to reductions in capital costs for capture technologies and in transport and storage costs.

Over time, **manufacturing sectors** will adopt CSS – particularly in industries like cement, steel, and chemicals – where process emissions are hard to eliminate and CCS is often the only viable solution. We forecast these sectors, including applications for heat production, will account for 41% of all captured CO_2 emissions in 2050.

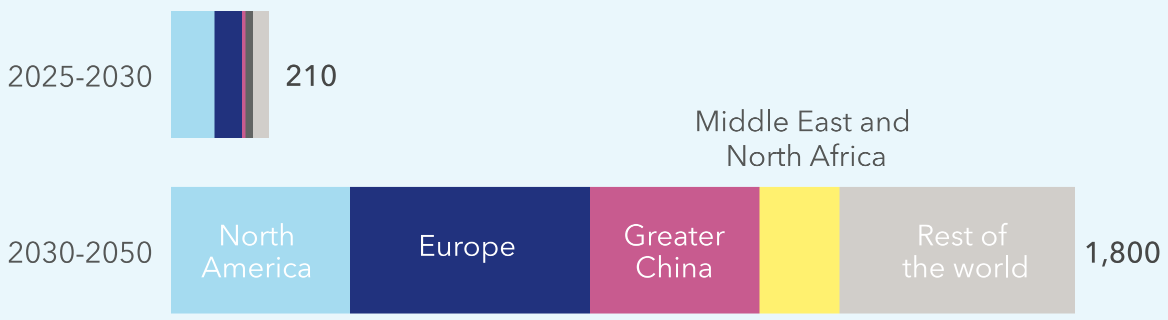
Compliance and voluntary offset markets will drive **carbon dioxide removal** to 330 $MtCO_2$/yr by 2050. **Bioenergy with carbon capture and storage** (BECCS) will begin scaling in the 2030s, primarily in electricity generation and manufacturing. Despite higher costs, **direct air capture** (DAC) will scale up to 84 $MtCO_2$/yr by 2050.

CCS grows to more than a gigatonne per year by 2050

Carbon capture and storage ($MtCO_2$/yr)

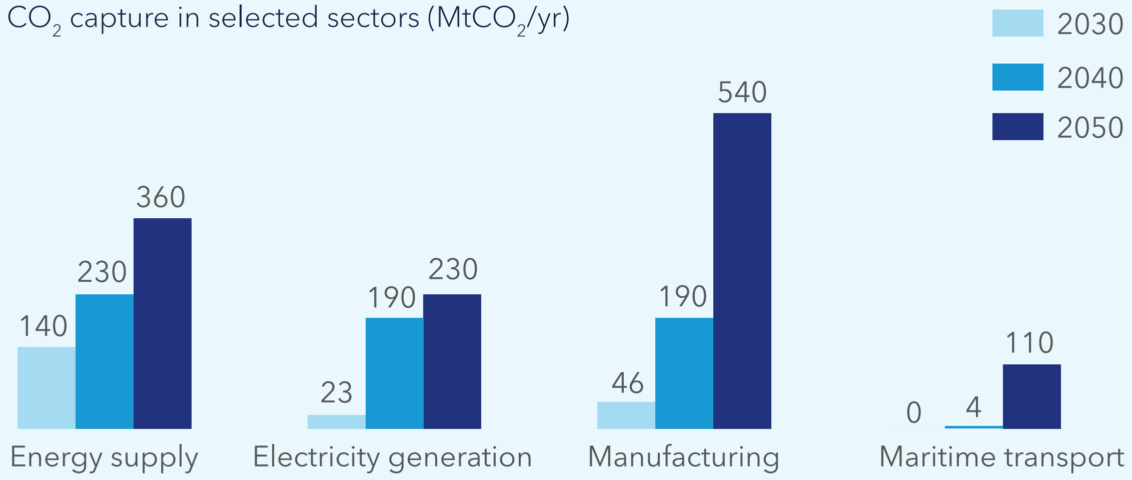
Europe and North America lead uptake

Capacity addition by region ($MtCO_2$/yr)



Timelines differ across sectors

CO_2 capture in selected sectors ($MtCO_2$/yr)



How robust is our 2030 CCS increase?

CCS is at a turning point. We expect global capacity to quadruple by 2030. Using various industry databases as a starting point, we forecast **270 $MtCO_2/yr$** of risk-adjusted **operational capacity** by 2030, with **210 $MtCO_2/yr$** of actual **CO_2 captured and stored** in 2030, based on utilization assumptions. Why do we feel reasonably confident that this level of deployment will materialize?

CO_2 receiving terminal in Øygarden, Norway. Photo: Screen Story / Northern Lights.

1. **Operational capacity and projects in construction.** Our outlook is supported by a strong project pipeline: 62 $MtCO_2/yr$ is already operational, 44 $MtCO_2/yr$ is under construction, and additional projects are reaching final investment decision (FID) regularly. With CCS projects typically requiring two to three years from FID to operation, 168 $MtCO_2/yr$ of additional capacity is highly likely to come online this decade. In early 2025, we saw multiple FIDs, including Stockholm Exergi (0.8 $MtCO_2/yr$), Ascension Blue Point (2.3 $MtCO_2/yr$), and transport and storage projects such as Northern Lights Phase 2, which will increase capacity to 5 $MtCO_2/yr$, and HyNet Phase 1, which will add 4.5 $MtCO_2/yr$ of transport and storage (T&S) capacity. Notably, most major T&S projects are designed to serve multiple emitters, meaning their commissioning unlocks broader capture deployment.

2. **Government commitments**. Geographically, the majority of expected CCS capacity growth to 2030 will occur in North America and Europe, regions with established policy support and regulatory frameworks. In the case of the US, while the White House recently signalled support for CCS (American Press, 2025), a degree of policy uncertainty persists at both federal and state level. However, we expect that 45Q support for CCS is likely to remain largely unchanged. Significant commitments made by governments around the world include: the UK targeting 20 to 30 $MtCO_2/yr$ of capacity by 2030, Canada 271 $MtCO_2/yr$, the US 110 $MtCO_2/yr$, Brazil 45 $MtCO_2/yr$, Australia 25 $MtCO_2/yr$, and Malaysia 15 $MtCO_2/yr$. In some jurisdictions these goals are supported by legal mandates. For example, the EU's *Net Zero Industry Act* requires selected oil and gas companies to collectively develop 50 $MtCO_2/yr$ of CO_2 storage capacity by 2030 (EU, 2025). CCS is also embedded in many countries' nationally determined contributions.

3. **Corporate momentum is equally strong**. Industry leaders – including ExxonMobil, Shell, BP, Chevron, and Aramco – have announced individual CCS targets ranging from 10 to 30 $MtCO_2/yr$ by 2030. These corporate pledges signal a growing alignment between commercial strategies and climate targets.

4. **Investment activity is intensifying**. Major investments and acquisitions related to CCS are becoming more frequent and substantial. In 2023, ExxonMobil acquired Denbury for USD 4.9bn, gaining access to its CO_2 pipeline infrastructure (ExxonMobil, 2023). SLB acquired a majority stake in Aker Carbon Capture (SLB, 2024), while Occidental purchased Carbon Engineering for USD 1.1bn, followed more recently by its acquisition of a second DAC company, Holocene (ESG Today, 2025). These moves demonstrate rising investor confidence and mark a shift toward the commercial maturation of CCS and related technologies.

In short, our capacity forecast for 2030 is empirically defensible, but more importantly for the medium and long term, the critical elements for scale – projects, policy, capital, and corporate action – are aligning. While political uncertainty might be one of the biggest risks to the realization of our forecast, the CCS inflection point is here.

> Our outlook is supported by a strong project pipeline: 62 $MtCO_2/yr$ is already operational, 44 $MtCO_2/yr$ under construction, and additional projects are reaching final investment decision regularly.

How we model CCS uptake

In our forecast, CCS uptake prior to 2030 is driven by a conservative pipeline of projects developed considering various industry databases at the time of writing. We have identified total capture capacity of projects with a pre-2030 start date of 313 $MtCO_2$/yr. We have adjusted the capacities and expected start years to account for their development status, recognizing that early-stage projects face a higher risk of delay or cancellation. Projects lacking any capacity estimate or start year have been excluded.

Starting from 2030, we allow the model to add CCS capacity beyond the project pipeline based on the comparison of cost of CO_2 avoided and the carbon price. However, in the 2030s, when the carbon price is still weak, we incorporate regional support mechanisms (OPEX and/or CAPEX policy support) to stimulate the uptake of projects. Support mechanisms for CCS help lower the cost calculus considerably in some regions (see Table 5.1). These support mechanisms include subsidies per tonne of CO_2 stored, state funding for CCS transport hubs, and tax breaks. This also includes CCS-related infrastructure projects where states bear the cost of infrastructure and the running costs for a certain period (e.g. the Northern Lights project in Northern Europe).

In the longer term (late 2030s and beyond), the adoption of CCS technology is purely a cost-driven process constrained by uptake speed limitations in our ETO model. Two underlying mechanisms significantly impact the cost calculus: the long-term decline in the levelized cost of CCS – i.e. the cost of CO_2 avoided by CCS – and the rising carbon price/cost. Emitters will compare the costs of adopting CCS with the cost of emitting CO_2 and paying the carbon price, and choose whichever costs less. This leads to an increasing appetite for CCS adoption. We have also introduced regional growth rate limits to reflect practical constraints in scaling up CO_2 transport and storage infrastructure. Although empirical data on CCS-specific growth limits are scarce, we draw on analogies from other large-scale infrastructure roll-outs, such as LNG, renewables, and pipeline networks. Based on these, we assume that CCS capacity can grow rapidly in the early phases, with a maximum annual growth rate of up to 90%, that gradually tapers to around 6% per year as the system matures and saturation effects set in.

The uptake of carbon dioxide removal technologies (BECCS and DAC) is driven by supply-demand dynamics within compliance and voluntary offset markets (see Section 4.4 for a more detailed description).

Table 5.1 provides further explanations of policy factors driving CCS uptake in the model. For a detailed discussion on policy factors influencing the global energy forecast, refer to DNV's *Energy Transition Outlook 2024* (DNV, 2024a).

> Two underlying mechanisms significantly impact the cost calculus: the long-term decline in the levelized cost of CCS – i.e. the cost of CO_2 avoided by CCS – and the rising carbon price/cost.

FIGURE 5.1
Carbon price by region

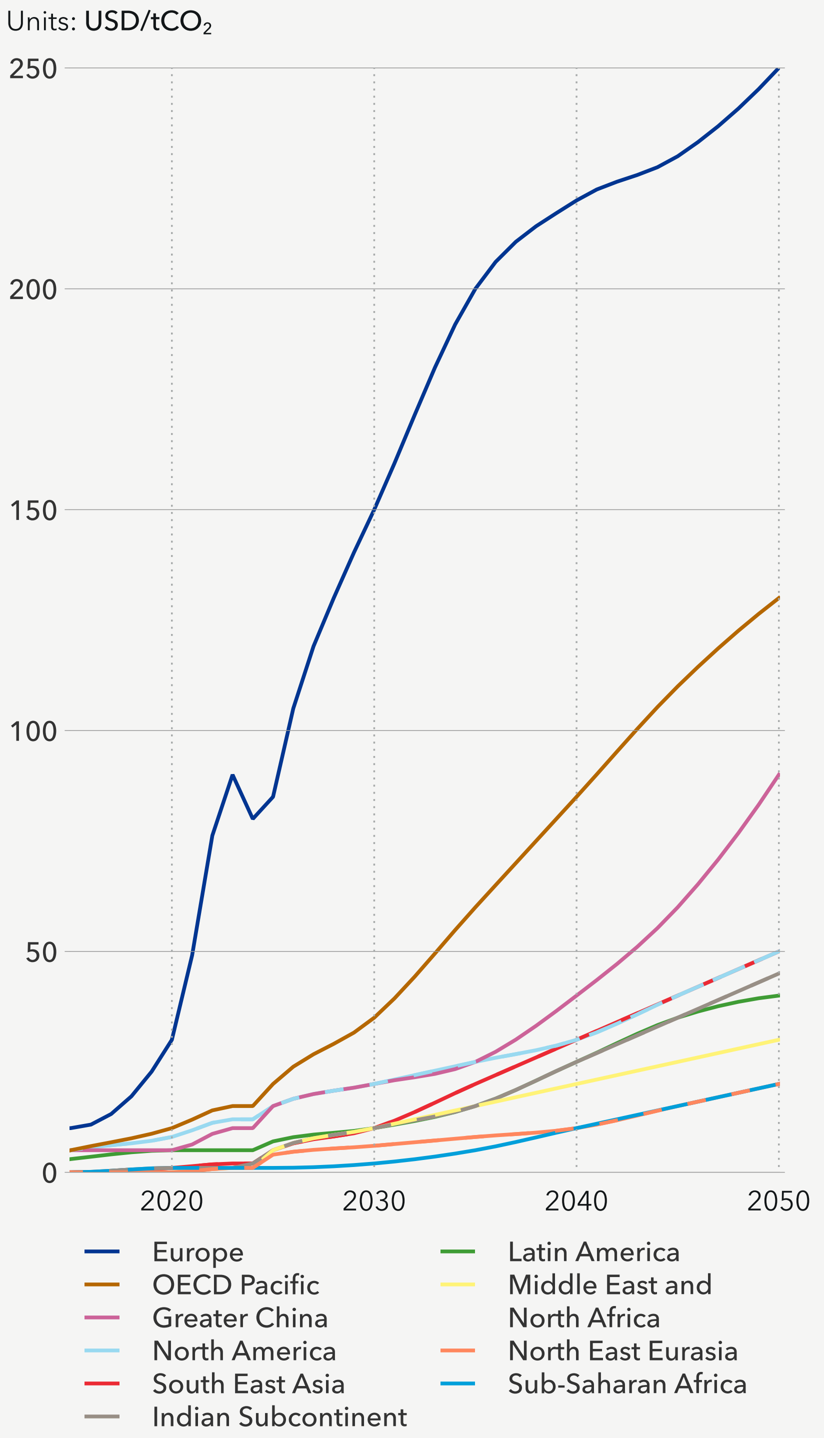


TABLE 5.1
Details on policy factors driving CCS uptake in the ETO model

Carbon capture and storage & direct air capture support

- Historical CCS implementations and the future project pipeline of capture and storage capacity through 2032, are incorporated into our model. These projects are the 'policy-driven' capacity expectations receiving investment and operational support from governments. We adjusted the reported pipeline to account for project capacity in an advanced phase of operation/construction and consider that some earlier phase projects will have delays and/or be discontinued.
- Regional policy support for CCS beyond the pipeline is integrated to enable initial CCS uptake. This is based on the assessment of current targets and funding announcements for projects' capital or operating expenditures. These factors indicate country/regional willingness to support until the CCS cost curve intersects with projected future carbon prices. This support is included either as a percentage subsidy for the capital cost or as USD/tCO_2, such as the 45Q tax credit in the US (which also distinguishes between capture-storage and capture-utilization; we assume this tax credit will stay in place). Policy support is reduced when the gap between carbon price and CCS costs narrows.
- Direct air capture support reflects established policy in the North America region. In the US, the IRA (2022) increased the 45Q tax credit to USD 180/tCO_2 captured via DAC for storage. We have implemented this in our model as subsidies in the region.

Carbon pricing schemes

- In the long term, carbon pricing, implemented either through a tax on carbon emissions or via an emissions trading system (ETS), will be the main driver and market-based instrument to incentivize emission reductions.
- Our regional carbon price trajectories are presented in Figure 5.1 and recapped in Section 4.1. For further discussion of global carbon pricing, please see DNV's global *Energy Transition Outlook* (DNV, 2024a).
- Regional carbon prices determine the uptake of CCS in power, manufacturing, and industrial processing. The trajectories are reflected as costs for fossil fuels in manufacturing, and in power, hydrogen, ammonia, and methanol production where we assume progressive participation in the same regional and/or sectoral carbon pricing schemes.
- Carbon price exemptions: We have reflected carbon price exemptions available to many industries and a lack of carbon prices in jurisdictions inside our regions. For Europe, we assume exemptions to be removed by 2034 in line with EU CBAM policy. For North America, manufacturing sector carbon prices apply to roughly 50% of industries on average throughout our forecast horizon.

Hydrogen support

- CCS in low-carbon hydrogen production is mainly driven by regional carbon prices. The main trigger for CCS uptake will occur when carbon prices are higher than the cost of CCS.
- In addition, regional policies that provide specific support for CCS will enable the initial uptake and reduce costs. This policy support will be reduced when carbon prices become high enough to sustain growth. For the North America region, the US supports blue hydrogen production via either the 45Q (see the CCS section of this table) or the 45V tax credits[1]. We assume a common level for either of the two tax credits, given that qualifying projects apply for whichever tax credit yields the highest support level.

[1] At the time of writing, it is proposed that 45V will be removed as part of the current administration's energy policy changes.

5.1 COST TRAJECTORIES

Currently and in the near term, the cost of CCS remains high, often exceeding USD 100/tCO_2 avoided – that is, the net cost of reducing emissions compared with a baseline option with no CCS and after accounting for the CO_2 emitted during the capture process – for both power and industrial applications. In some sectors, such as oil refineries, costs can rise well above USD 200/tCO_2 avoided. These figures reflect total CCS costs, including capture, compression and/or liquefaction, and transport and storage (T&S).

There are notable exceptions: in industries like ammonia and ethanol production and natural gas processing, where CO_2 capture is an inherent part of the production process, costs are significantly lower due to the high purity of CO_2 streams. In these cases, CCS costs typically fall below USD 100/tCO_2 avoided.

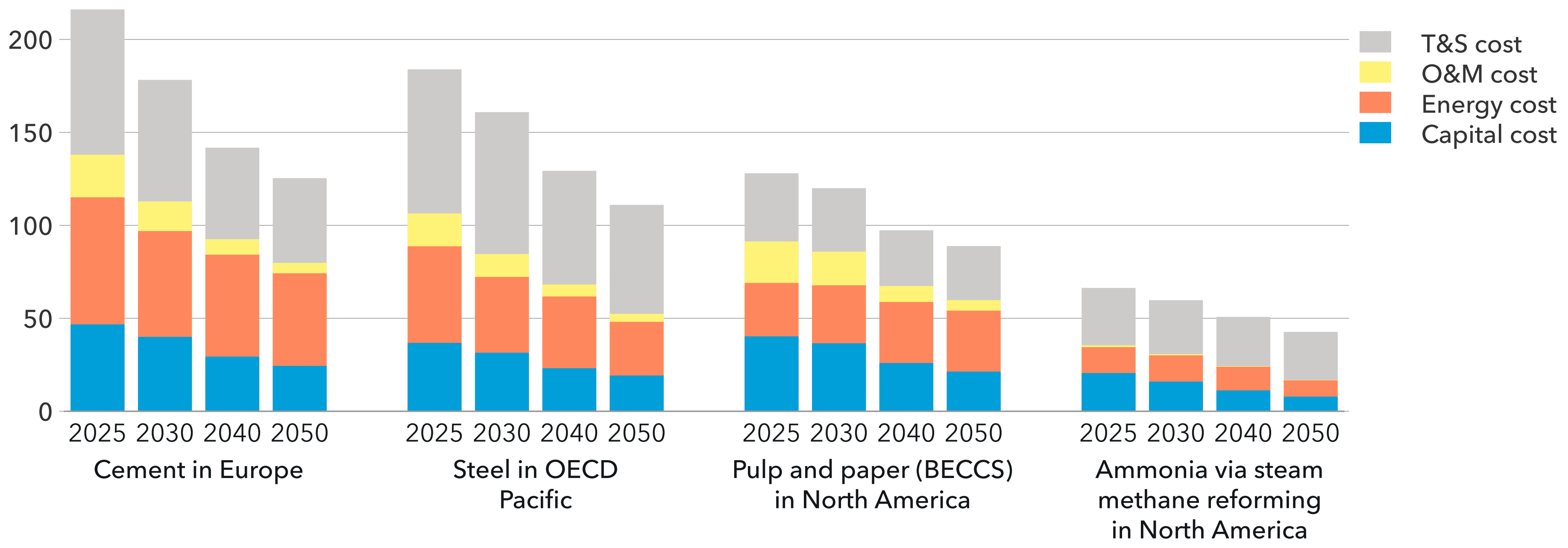
CCS costs also vary significantly by region, largely driven by differences in energy prices and T&S methods and cost components.

Looking ahead, with the pipeline of CCS projects currently under development expected to come online in the next few years, we anticipate an average cost reduction of around 14% by 2030. Over the longer term, as CCS deployment scales across regions and sectors, we forecast that the average cost of CO_2 avoided could decline by approximately 40% by 2050. These reductions will be driven primarily by declining capital costs for capture technologies and lower T&S costs as infrastructure matures and economies of scale are realized.

FIGURE 5.2

Cost of CO_2 avoided for selected industrial applications and regions

Units: USD/tCO_2



Cost of capture

Figure 5.2 illustrates our forecast trajectory of CCS costs – expressed as the cost of CO_2 avoided – for four selected industrial applications in regions where we expect these applications to generate sizable volumes of captured CO_2.

Beyond T&S costs (discussed further below), capital and energy costs represent the largest share of total CCS costs. We project consistent capital cost reductions across applications and regions: an average 15% decline by 2030 and up to 50% by 2050, relative to current levels. These reductions are driven by economies of scale as deployment expands; by modularization and standardization, especially in the near term; and technological advancements in capture systems. Our analysis assumes a 13% learning rate with each doubling of installed capture capacity, which is lower than the learning rates we assume for solar PV and wind power, for example.

The energy required for CO_2 capture, compression, and/or liquefaction is a significant contributor to overall CCS cost. The ratio of energy cost to capital cost varies by sector, largely due to differences in energy penalties associated with specific applications. However, the absolute level and trend of energy costs is primarily influenced by regional fuel price forecasts. For this reason, energy costs for CCS in cement production are somewhat higher in Europe than for CCS in steel production in the OECD Pacific, despite the fact that CCS in steel may be more expensive within a given region. In contrast, ammonia production via steam methane reforming has notably lower energy costs due to the high purity of CO_2 in the process stream, making it one of the more cost-effective CCS applications.

BECCS in the pulp and paper sector, as shown for North America, represents a mid-range CCS application in terms of cost. The current cost of capture and compression is approximately USD 90/tCO_2 avoided, projected to decline to below USD 60/tCO_2 avoided by mid-century.

While non-energy operations and maintenance (O&M) costs make up a relatively small portion of total CCS costs, we also expect them to decline over time. We assume a 15% learning rate for this component with each doubling of capacity. O&M cost reductions tend to outpace capital cost reductions, due to advantages like process optimization, operational experience, and digital technologies, whereas CAPEX is tied to physical infrastructure that improves more slowly.

CCS in power

In the context of CCS for power generation, we distinguish between retrofits and new builds, as the underlying business models, technical constraints, and cost dynamics differ significantly between the two.

While the cost of CO_2 avoided remains a key metric for tracking CCS cost trends over time, it should primarily be understood as a decision-making tool for prospective CCS operators that helps to assess whether investing in CCS is economically justified compared to operating without it.

To explain cost dynamics futher, Figure 5.3 illustrates the Levelized Cost of Electricity (LCOE) trajectory for coal-fired power plants in Greater China as well as the unit variable operating costs. Figure 5.4 shows the cost of CO_2 avoided for both retrofits and new builds with CCS.

LCOE for CCS retrofits is currently modestly higher than for new builds – USD 110/MWh vs USD 93/MWh, respectively. This is mainly due to the higher capital costs associated with retrofitting existing infrastructure. However, retrofits benefit from avoiding the capital costs of the original plant and may also save on permitting and administrative costs. Despite this, both retrofits and new builds with CCS are approximately 38% more expensive than new unabated fossil power plants. This is primarily due to higher capital expenditures and operating costs arising from the energy penalty associated with CO_2 capture and compression.

Looking ahead, we forecast a decline in LCOE towards the late 2030s, followed by a sharp increase. We foresee modest LCOE reductions of about 3% by 2030 and 13% by the late 2030s for CCS-equipped new builds, largely driven by declining capital cost of CCS through technology learning effects. After the late 2030s, as solar and wind generation capacity expands, capacity factors of thermal power plants will decline, leading to a rise in LCOE (as the investment cost is spread over fewer operating hours). While we differentiate between capacity factors of plants with and without CCS based on their variable costs, in this case, the additional cost of capturing carbon roughly matches the carbon price in China. This leads to a similar trajectory of capacity factors for the two types (Figure 5.3). However, for CCS retrofit plants, there is an additional factor that further increases the LCOE: the remaining lifetime of the underlying asset. While the average lifetime of coal-fired power plants in China today is 15 years, it will surpass 25 after 2040, shortening the economic lifetime of carbon capture on older plants and making CCS retrofits even less appealing. We also see this phenomenon happening earlier in regions like Europe. A third differentiating factor between power plants with and without carbon capture will be the cost of capital. We foresee the cost of capital for CCS reducing as the technology is proven and matures, while the cost of capital for unabated power plants will rise, even before 2030.

The rising carbon and borrowing cost burden on unabated plants, combined with declining capacity factors, will lead to a convergence and eventual crossover in LCOE. As a result, we expect new fossil power plants with CCS to become more cost-competitive than unabated ones, with the cost of CO_2 avoided turning negative starting in the late 2030s.

For retrofits, the capital cost component of LCOE will increase more gradually in the 2040s, since total capital investment is significantly lower: roughly 67% less than that of a new CCS-equipped plant. However, the benchmark for retrofit comparison is the existing unabated plant, which incurs no new capital cost. Therefore, the LCOE of the retrofit will always be higher than that of the original plant, and the cost of CO_2 avoided will remain positive. Moreover, as capacity factors decline and remaining lifetimes are reduced for both retrofitted and unabated plants, the cost of CO_2 avoided for retrofits will even increase in the 2040s (Figure 5.4).

FIGURE 5.3

LCOE and expected variable unit cost for coal-fired power plants in Greater China

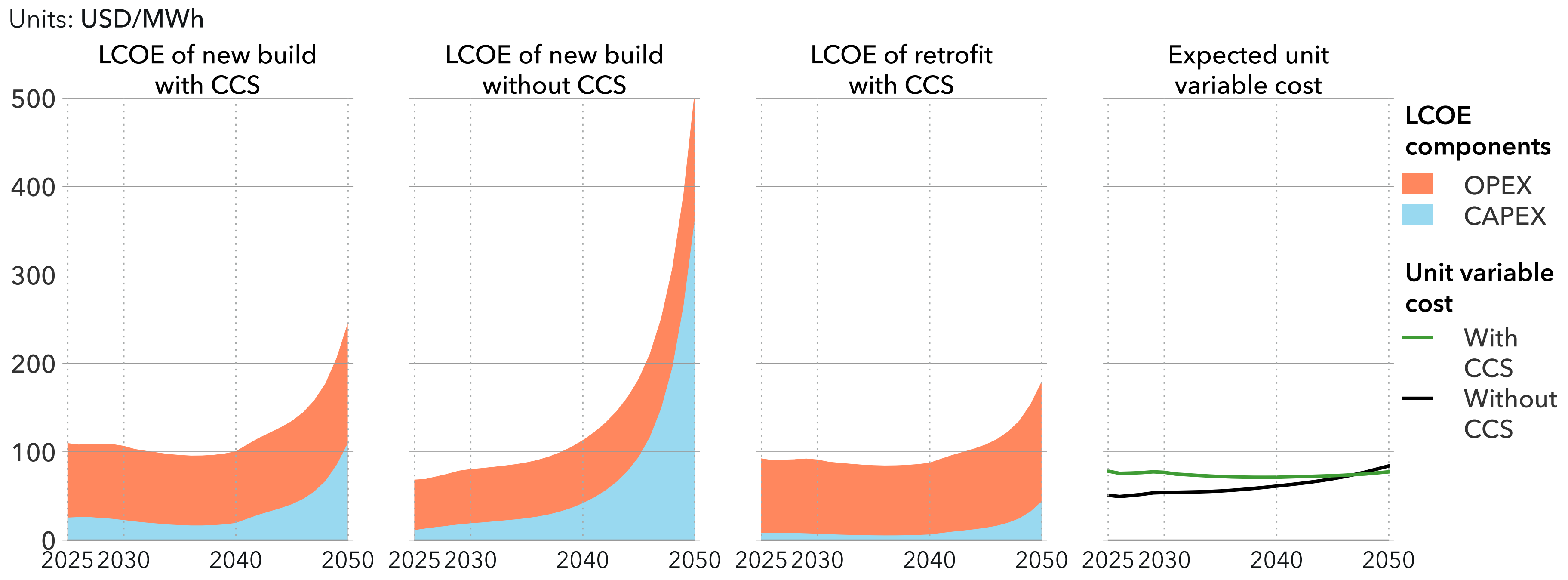
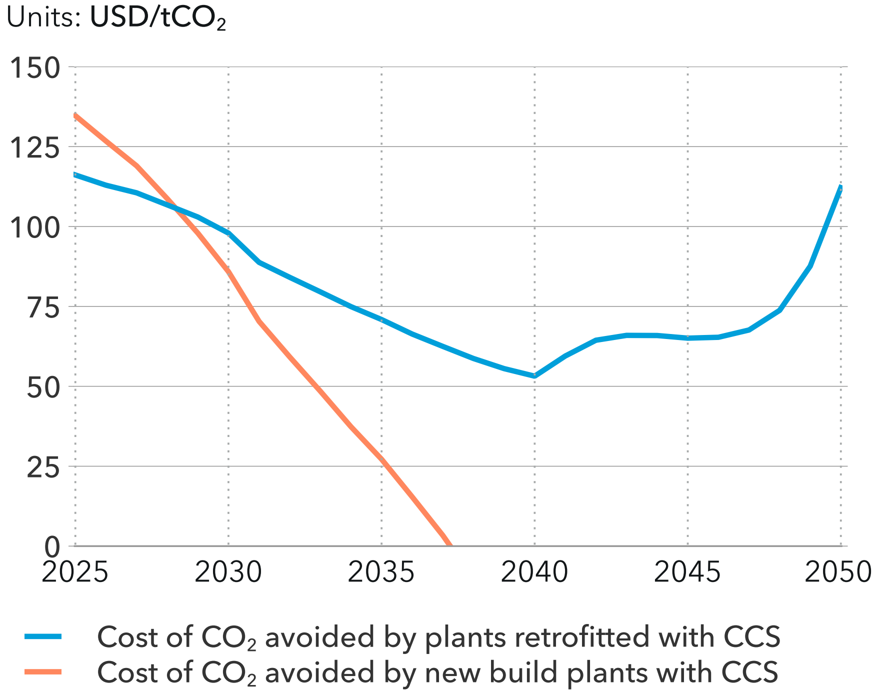


FIGURE 5.4

Cost of CO_2 avoided by CCS for coal-fired power plants in Greater China



T&S costs

T&S costs account for approximately 25% to 35% of the total cost of CO_2 avoided, varying by the region and sector where CCS is applied. In lower-cost CCS applications, such as natural gas processing and ammonia production, T&S can represent a significantly larger share of the overall cost, ranging from 50% to as high as 70%. Consequently, reducing T&S costs will play a critical role in driving down the overall cost of CCS. For example, in Europe, where T&S costs are among the highest, we project a 17% reduction by 2030 and a 43% reduction by mid-century (see Figure 5.5).

Storage costs

North America enjoys the lowest storage costs, around USD 17/tCO_2, largely due to its use of onshore storage and extensive experience with enhanced oil recovery (EOR). In contrast, Europe's storage costs are higher, approximately USD 23/tCO_2, owing to its reliance on offshore storage in the near to medium term. We project storage costs for South East Asia and the OECD Pacific region to be similar to those in Europe, with slightly higher costs in India and Greater China of around USD 25/tCO_2.

Storage cost reductions will be modest in North America (about 4% by 2030 and 19% by 2050), given the maturity of the existing EOR industry and limited potential for technological breakthroughs or site improvements. In Europe, however, we expect more significant cost reductions, around 9% by 2030 and 28% by 2050, due to advancements in offshore storage technology and increasing CO_2 injection rates as CCS deployment scales up.

Transport costs

In North America, where CO_2 storage is primarily onshore, CO_2 is typically transported using pipelines. In regions like Europe, where offshore storage dominates, multimodal transport systems are often necessary. These result in higher costs. At present, CO_2 transport in Europe is roughly twice as expensive as in North America.

We expect this disparity to narrow over time. As Europe's T&S networks expand, we project transport costs will decline by 18% by 2030 and 37% by 2050. In the later decades, the emergence of onshore storage options, supported by increasing public acceptance of CCS, will further drive down transport costs. In North America, where onshore storage is more established, we expect only a 4% reduction in transport costs by 2030. However, as offshore storage becomes more widely utilized in the 2030s, transport costs will rise, with a projected overall increase of 11% by 2050 compared to today.

T&S tariffs and total cost to emitters

Our analysis adopts the perspective of the emitter. In this framework, the operator of a CO_2 capture facility pays a T&S tariff to a third-party provider managing the T&S network. This tariff includes not only the direct costs of transport and storage, but also a margin covering profit, project risks, contingencies, and other factors discussed in Section 2.4.

Currently, in North America, the T&S tariff charge comprises about 33% of the total T&S cost, reflecting the more established industry and infrastructure. In contrast, Europe's tariff makes up about 58% of total T&S cost, due to higher risks and early-stage inefficiencies tied to offshore storage and the potential for higher-complexity multimodal transport systems. In some sectors – such as ammonia, hydrogen, and natural gas production, as well as oil refining – vertically integrated CCS projects can significantly reduce the T&S tariff charge, in some cases by up to 50%.

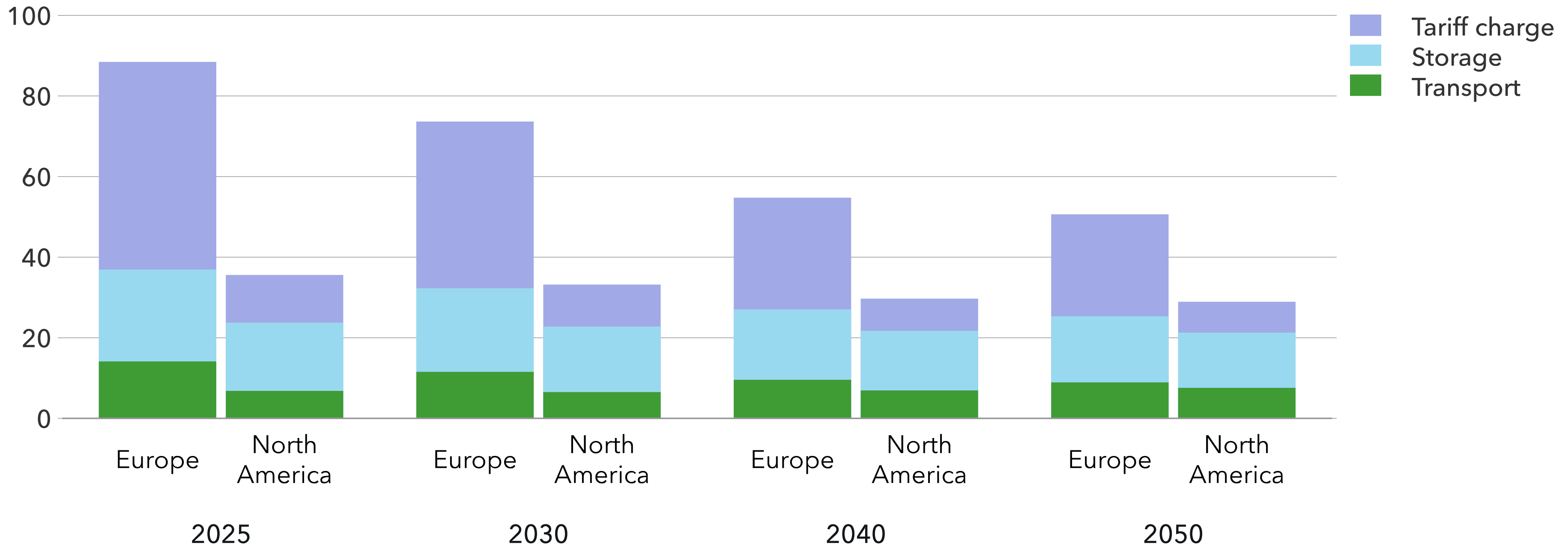
While the tariff charge is a major component of total T&S costs, it also presents the greatest opportunity for cost reduction. As projects mature and risks decline, we expect substantial improvements. In North America, we forecast T&S tariff charges to fall 12% by 2030 and 35% by 2050. In Europe, the reductions will be even more pronounced: 20% by 2030 and 51% by 2050.

> As Europe's T&S networks expand, transport costs are projected to decline by 18% by 2030 and 37% by 2050.

FIGURE 5.5

Transport and storage costs in Europe and North America

Units: USD/tCO_2



5.2 UPTAKE BY SECTOR

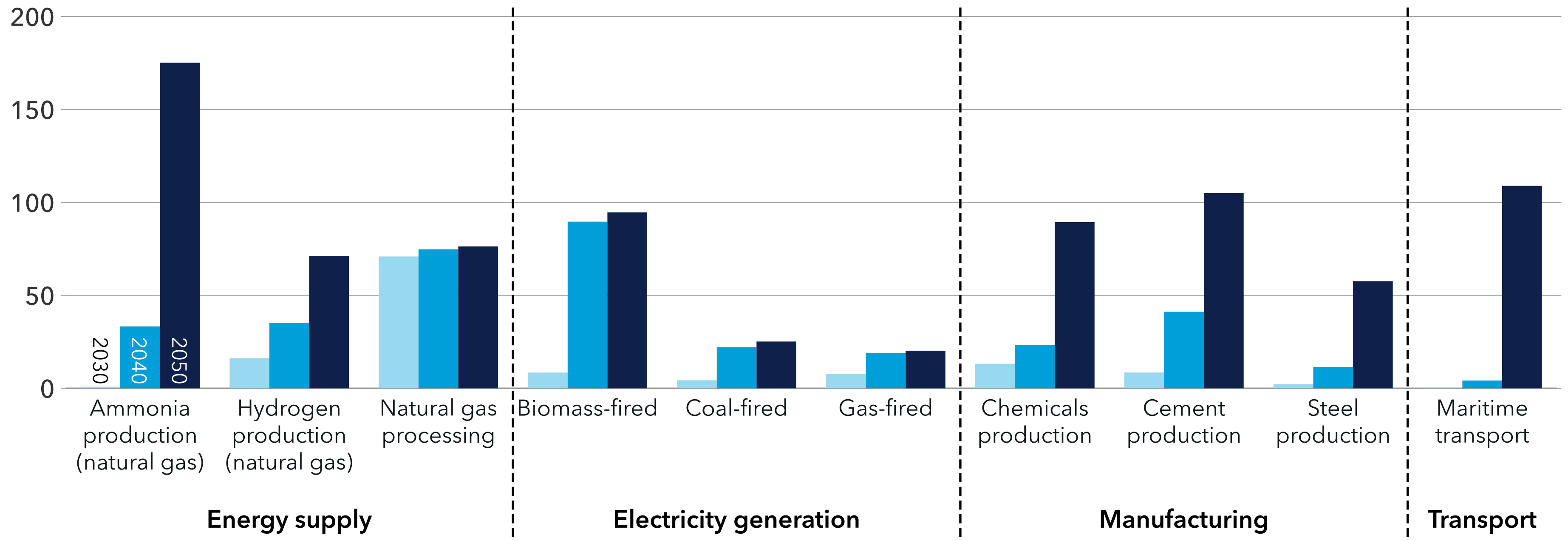
By 2050, we expect 1.3 $GtCO_2$/yr will be captured and stored – a more than 30-fold increase from the current volumes. However, this strong increase is not uniform across sectors; we see some early-moving sectors stagnating while other sectors come on strongly towards the end of this period.

Carbon capture is currently installed at scale in natural gas processing, mostly as capture for EOR. Up to 2040, hydrogen as an energy carrier, electricity from biomass, and cement will be the next sectors driving uptake (Figure 5.6). Global deployment increases steadily through 2050 as CCS becomes more attractive for more industrial sectors. From the mid-2040s, we see broader industrial contributions and specific growth in maritime transport. We also see an early growth and later reduction trend for global ethanol production, even as Latin America builds further regional capacity throughout the period.

FIGURE 5.6

CO_2 captured in selected sectors, representing more than 75% of total capture in 2050

Units: $MtCO_2$/yr



CO_2 tanks at the Heidelberg Materials cement plant in Brevik, Norway. Photo: Heidelberg Materials AG.

Energy supply

Ammonia

Most of the ammonia produced as an energy carrier is produced from natural gas. The first natural gas-based ammonia production sites with CCS (low-carbon ammonia) will start operating around 2030 (Figure 5.7).

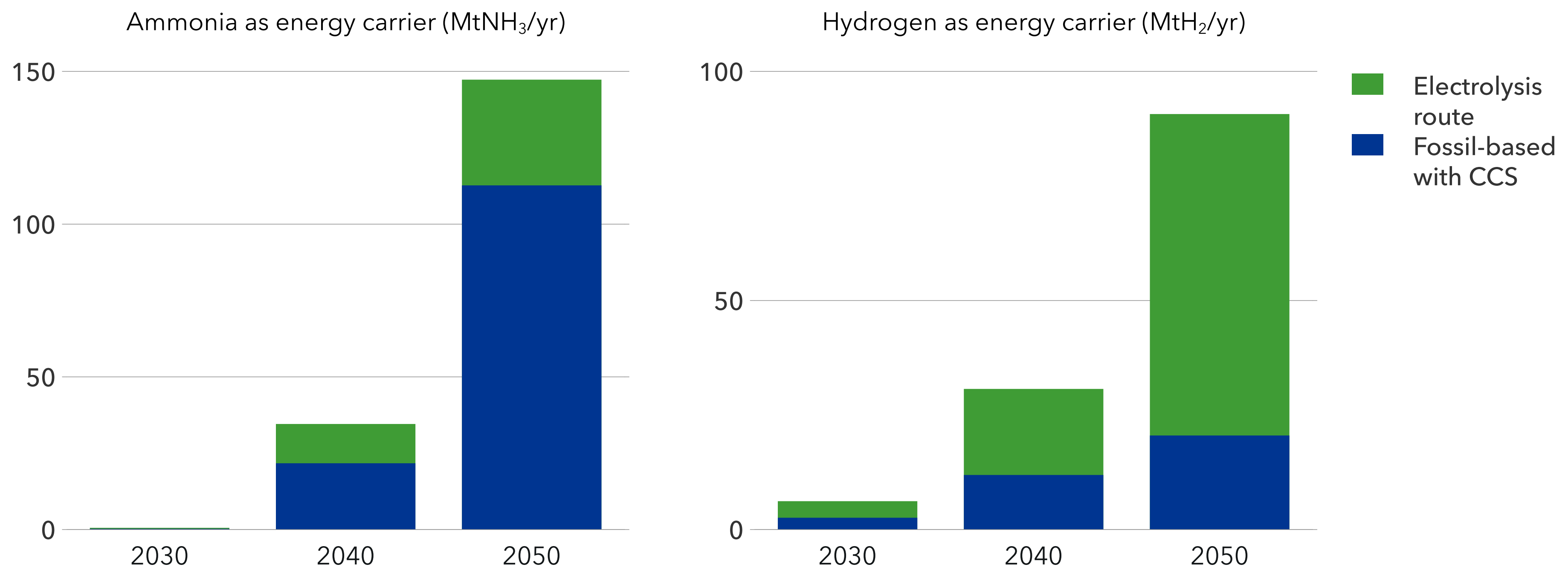
North America is the first mover in this sector because of policy support and existing CCS infrastructure and competence. After moderate sector growth in the first part of the period, the region sees a five-fold growth from 2040 to 2050. North America will lead CCS in ammonia throughout the period to 2050, with a consistent share up to 80% in 2050. This represents almost 160 of the 200 $MtCO_2$/yr captured in ammonia production in 2050.

The Middle East and North Africa will experience steady capture growth through the 2040s. The volume of ammonia produced with CCS will meet maritime demand in the region and offer some capacity for other production and export.

Our ammonia numbers include a share of CO_2 captured during production of ammonia used for fertilizer.

FIGURE 5.7

Competition between CCS and electrolysis routes for hydrogen and ammonia as energy carriers



Hydrogen

We expect strong competition between renewables-based hydrogen (from electrolysis) and low-carbon hydrogen with CCS. Low-carbon hydrogen is produced from natural gas with steam methane reforming coupled with CCS. As shown in Figure 5.7, low-carbon hydrogen will be more competitive in the first decades. The position of natural gas will remain strong for ammonia production, but electrolysis will gradually take over from natural gas in hydrogen production. Hydrogen production from natural gas will account for 14% (including feedstock) of the CO_2 captured both in 2040 and 2050.

Low-carbon hydrogen with CCS grows steadily in North America through 2050 and will dominate hydrogen from renewables up to the early 2030s. The hydrogen in North America will be sold in the local markets that accept low-carbon hydrogen and exported to Europe where countries want to diversify their energy dependence.

We see Europe and the Middle East and North Africa building capture capacity in hydrogen production from 2030 onwards. Europe is doing this to fulfil its strong ambitions on emission reductions, but the capacity additions here are lower. The Middle East and North Africa have abundant volumes of natural gas and will use this for hydrogen production, both with and without CCS. CCS in hydrogen production will grow the most in this region, and by 2050 the Middle East and North Africa will surpass North America in this sector. Together, these two regions capture two thirds of the global volumes of CO_2 captured from hydrogen in 2050, while Europe takes an additional 11%. At the same time, the Gulf countries are investing heavily in renewables with the aim of also producing renewables-based hydrogen. This hydrogen will not be price competitive in the Middle East and North Africa, but it will provide hydrogen that complies with the lower emission footprint requirements of certain customers.

Natural gas processing and oil refineries

In 2024, two-thirds of CO_2 captured was associated with decarbonizing emission sources within the energy sector. This was mostly for processing natural gas, but also included a small volume from capture in oil refineries. Most of the CO_2 captured was stored through EOR, an application which the oil and gas industry has used for many years to increase oil production. Where there is appropriate geology, EOR increases oil production while also trapping CO_2 in the subsurface. Looking forward, we expect CCS in natural gas processing to more than double in the coming five years to just above 70 $MtCO_2$/yr before slowing. By this, the share of natural gas processing in total capture will fall continuously, from 34% in 2030 to 6% in 2050.

From 2030 and onwards, the uptake of CCS in this sector is split between many regions with North America and South East Asia as the biggest, followed closely by the Middle East and North Africa.

Electricity generation

Bioenergy with CCS (BECCS)

BECCS captures biogenic CO_2 emissions to deliver net-negative emissions. BECCS in power will grow to account for 15% of the emissions captured in 2040. After this, the volumes level out and the share of the sector reduces to 8% in 2050 as other sectors expand. Today, carbon dioxide removal is primarily incentivized through the voluntary carbon market.

We anticipate carbon dioxide removal being incorporated into compliance markets increasingly over the forecast period, and this strengthening the business case for BECCS (see Section 5.3 for further discussion of the BECCS business case). We find that most of the BECCS will take place in Europe, followed by the Middle East and North Africa, Greater China, and OECD Pacific.

Manufacturing sectors with the highest CCS uptake

Chemicals production

North America is an early adopter of CCS in petrochemical industries. The US draws on 45Q tax credits, existing infrastructure, and established regulatory frameworks for transport and storage. After 2040, Europe will capture more than North America and more than three-quarters of all captured CO_2 in this sector by 2050. Europe's dominance comes as a result of high carbon prices and regional emissions constraints. During this time, capture in this sector in North America will stay more or less constant.

Globally, CCS in chemicals production will grow from 7 $MtCO_2$/yr today to 110 $MtCO_2$/yr in 2050.

Cement production

CCS is currently the preferred method for abating CO_2 emissions at scale in cement production. Capturing post-combustion emissions could be facilitated by using oxyfuel combustion. However, the calcination process's emissions account for two-thirds of the sector's total emissions, so decarbonizing the fuel mix is insufficient.

We expect CCS in cement to scale in the early 2030s. Europe will lead the uptake, again, largely because of its high carbon prices and regional emissions constraints. Other regions will see more limited uptake. Europe will represent 72% of the sector's capture in 2050. Some of the front-runners in the region are Heidelberg Brevik (Norway), Heidelberg Antoing (Belgium), Cementa Slite (Sweden), and Holcim Obourg (Belgium). Several of these plan to deliver CO_2 to Northern Lights (Norway) for storage. Establishing these supply chains for transport and storage is crucial to facilitate wider CCS uptake in relevant industries. Altogether, the cement industry will account for 5% of the total capture in 2030 and 9% in 2050.

The cost of transport and storage will stay close to half of the total cost for avoiding CO_2 emissions (see Section 5.1). This could create a window of opportunity for the cement industry – traditionally focused on serving local markets – to consider relocating closer to CO_2 storage sites in the medium or long term (BCG, 2024).

Iron and steel production

The iron and steel production industry will capture 58 $MtCO_2$/yr by 2050. Most CCS in the sector will be installed in order to extend the lifetimes of traditional blast furnace plants (BOF). We also foresee some greenfield direct reduction – electric arc furnace

(DRI-EAF) plants with natural gas and CCS, like the recent Emirates Steel plant in Abu Dhabi. However, these greenfield CCS investments will be limited, as most of the new DRI-EAF plants plan to transition to green hydrogen after starting up using unabated natural gas (Steelradar, 2025). Scrap recycling in electric arc furnaces will be the alternative route for low-carbon steel production. Its share of the total production volumes will increase from 23% to 39% in this period.

The first clear volume growth in CO_2 capture in iron and steel production comes in the mid-2030s as Europe's uptake grows to meet the EU regulations. Europe's capture in this sector will peak around 2040 then reduce as BOF installations with extended lifetimes end operation and the market gets more recycled scrap from metal recycled by EAF.

From 2040, we expect strong growth in OECD Pacific following the ambitions of regional steel producers. Japan will lead this (Nippon Steel, 2024), with strong regional support from authorities to establish CCS supply chains (Asian CCUS Network, 2024). Following this growth, we project OECD Pacific to account for the largest share of global CO_2 capture in steel production, reaching 56% by 2050.

Greater China currently accounts for half of global steel production and operates a relatively young BOF fleet. However, the current low carbon price provides little incentive for investment in CCS. As a result, we expect the adoption of CCS in steel production in the region to remain lower than in

Clipper Eris, owned by Solvang ASA, is the first ship with a full-scale onboard carbon capture facility currently being tested. Photo: Solvang ASA.

North America for most of the forecast period. We only anticipate a more significant increase closer to 2050, as China places greater emphasis on achieving its 2060 carbon neutrality targets.

Transport

Maritime transport

Maritime transport is the only transport segment that will implement CCS, with initial deployment starting in the 2030s and scaling from around 2040. The maritime sector cannot, in general, electrify. Therefore, the primary pathway to significantly reduce emissions is to decarbonize the fuel by using green fuels on vessels or by capturing the CO_2 after burning fossil fuels. However, as the cost for green fuels is expected to be high, onboard carbon capture may be a competitive alternative even considering the additional costs for CAPEX, OPEX, and discharge. Onboard carbon capture is currently being tested on board several ships and the first batch of captured CO_2 was discharged to shore in 2024.

Our analysis shows that CCS is likely the less expensive option. However, it requires established infrastructure for offloading CO_2 in ports and subsequent transport and storage. This is a significant challenge. Still, we expect a system to be in place from 2040 and 15% of all maritime CO_2 emissions to be captured and stored by 2050. Overall, maritime transport will account for 9% of CO_2 captured with CCS in 2050. More details about onboard CCS can be found in our *Maritime Forecast* and white paper *The potential of onboard carbon capture in shipping*.

5.3 CARBON DIOXIDE REMOVAL

Our earlier forecasts, both the most likely future (DNV, 2024a) and particularly the challenging pathway to net zero (DNV, 2023b), demonstrate the need for carbon dioxide removal (CDR) to reach a net-zero future. The deployment of CDR supply is driven by both a required compliance carbon market and a voluntary market (see Section 4.4). This forecast meets the demand for CDR with BECCS and DAC (see the fact box under Section 2.1), both with permanent storage. Only technology-based CDR solutions are included in these numbers (not aforestation and reforestation, for example). Due to a rapid increase in demand as the carbon cost rises, the supply buildout will lag. In 2050, the annual emissions reduced through CDR will amount to 330 $MtCO_2$/yr, the majority of which will be removed in the Americas and Europe.

Compliance and voluntary demand differ

Compliance-driven demand assumes carbon credits must be cheaper than the regulatory carbon cost that alternatively must be paid for emissions. If carbon credits are cheaper, emitters will opt for them instead. Europe is projected to have the highest carbon cost and will initially drive compliance-driven demand, making up about two thirds of total CDR demand. In the 2040s, the carbon cost in the OECD Pacific region will also be high enough to drive compliance demand.

Voluntary demand depends on how many companies or individuals choose to offset their emissions, which in turn depends on the cost; their ability to pay; and, for businesses, the business value of being carbon neutral. This demand is mostly driven by companies with net-zero targets offsetting emissions from business air travel and buildings. We expect North America, Europe, and the OECD Pacific to have the highest number of companies initially seeking to offset their emissions through carbon credits, with Greater China following in the 2040s. As North America is projected to have the highest emissions among the three regions, we expect it to drive the greatest initial demand for voluntary carbon credits.

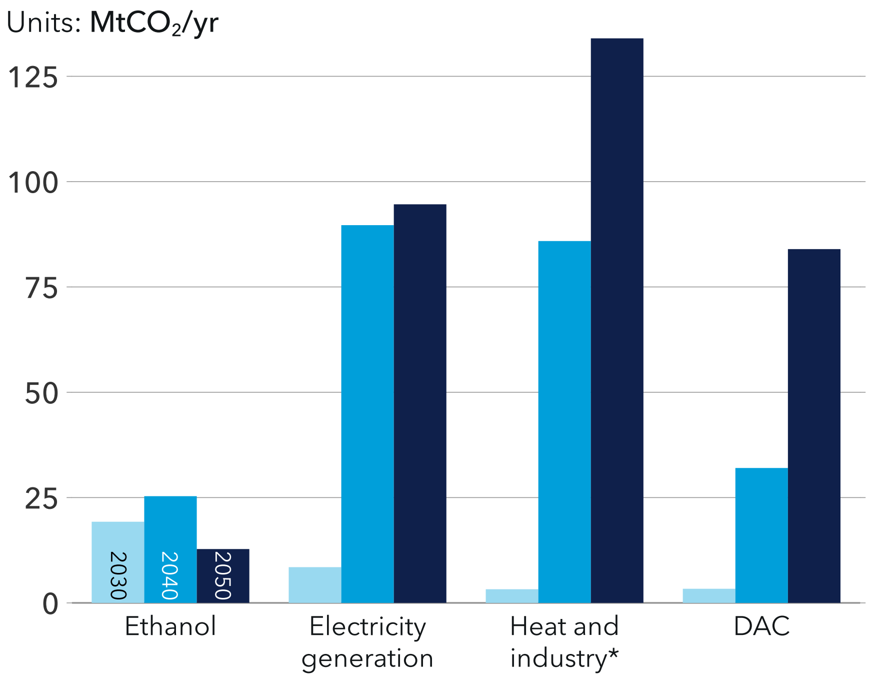
Carbon credits

We anticipate international agreements being in place to enable carbon credits to be generated in the most cost-effective locations and traded across regions, depending on the specific requirements of the scheme in place. Therefore, even though the demand originates mostly in Europe and North America, the carbon can be removed anywhere across the globe. This enables the cheapest capture options to develop first, thereby building up the industry.

For example, North America starts the uptake with a subsidy-driven supply of capturable CO_2 from the production of bioethanol. The subsidy is up to 85 USD/tCO_2 captured and stored from industry (Jones and Marples, 2023). Bioethanol production is also one of the cheaper options for BECCS. This combination leads to an expected early buildout of BECCS in bioethanol production in North America, up to a peak of about 26 $MtCO_2$/yr, limited by the levelling off of bioethanol production after 2040 (see Figure 5.8).

FIGURE 5.8

CO_2 removed in selected sectors



* About 10% of the captures in heat and industry are in building heating.

Several biomass-fuelled power plants are already scheduled to install carbon capture equipment. Our analysis forecasts BECCS growing in almost all regions. In the 2040s, BECCS in electricity grows less with the growth of solar and wind power. This development also contributes to BECCS in district heating of buildings. BECCS in industrial heating is initially limited, but will grow with the increasing carbon cost and an established carbon offset industry.

Direct air capture

DAC is generally more expensive than BECCS since it captures CO_2 from lower concentrations in the air, which is a more energy-demanding process. However, DAC will play an important role, given its deployment flexibility and the slower scale-up of BECCS, with the latter likely to place upward pressure on carbon credit prices. BECCS is mainly constructed by retrofitting existing plants, which can be far from storage sites. It is also limited by the amount of biogenic CO_2 available for capture. DAC does not face those limitations, as it can be built independently at select storage sites. Furthermore, both solid-sorbent and liquid-solvent DAC have the potential to streamline costs as deployment increases, detailed in the factbox under Section 2.1. This will gradually drive the capacity growth for DAC, particularly in the 2040s.

5.4 UPTAKE BY REGION

We project CCS – including CDR – to grow by more than 30-fold from 2024 to 2050, significantly reducing regional CO_2 intensity and supporting emission reductions in hard-to-decarbonize sectors. Adoption will vary by region due to policy, infra-structure, and cost differences, but over time, evolving incentives, knowledge transfer, and climate-driven trade will drive broader CCS uptake and boost the competitiveness of low-carbon commodities. While CCS is growing, it is not fast enough to meet anticipated decarbonization needs, with only 6% of CO_2 emissions expected to be captured through CCS in 2050.

Time is of the essence

In 2024, the total amount of CO_2 captured via CCS, including BECCS, was 41 Mt. By 2050, we project this to rise to 1.3 Gt. While North America accounted for about 42% of capture in 2024, we expect adoption to become more regionally diverse by 2050 due to differences in carbon pricing and technological progress. A temporal perspective is key to understanding regional CCS and CDR adoption trends.

Through 2030, CCS uptake will primarily be driven by projects already in development across various regions. From 2031 to 2050, further deployment will increasingly depend on regional decarbonization goals, prevailing carbon prices, and the evolving cost of CCS – shaped by learning effects and expe-rience from earlier projects.

In the near term, we expect North America – leading CCS deployment in 2025 (GCCSI, 2024c) – to continue expanding its capture capacity with the multitude of projects slated to come online in the next five years (Figure 5.9). The reasons for North American dominance in the short term are:

- Deep experience and knowledge base in imple-menting and operating carbon capture, transport, and storage of captured CO_2
- Lower costs due to time in the carbon capture, transport, and storage market
- Business-case of carbon capture for EOR de-risking the adoption of capture technologies
- Decades-long existence of infrastructure for transport and storage
- Recently, provisions in the US IRA enhancing 45Q, along with government support for CCS in Canada (Reuters, 2024)
- Clear laws and regulations with regards to transport and storage of CO_2 (both in saline aquifers and depleted oil and gas wells) (Chalmin, 2022)

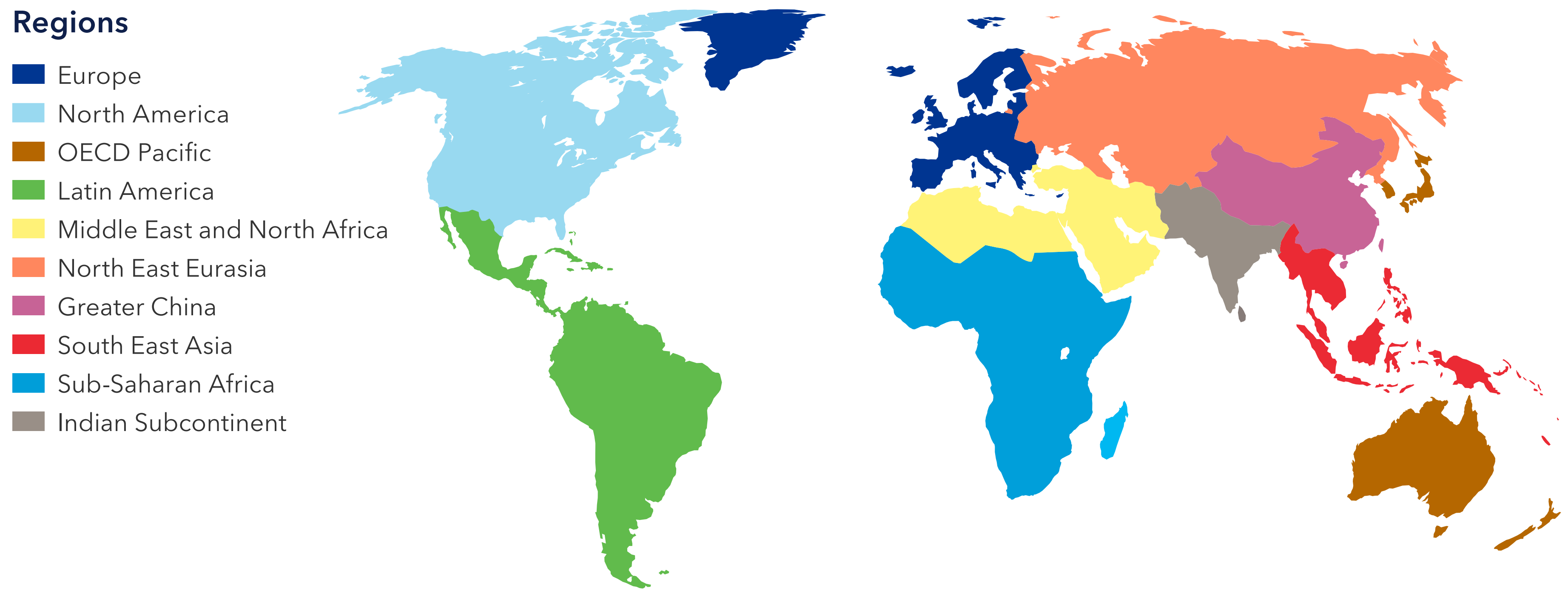
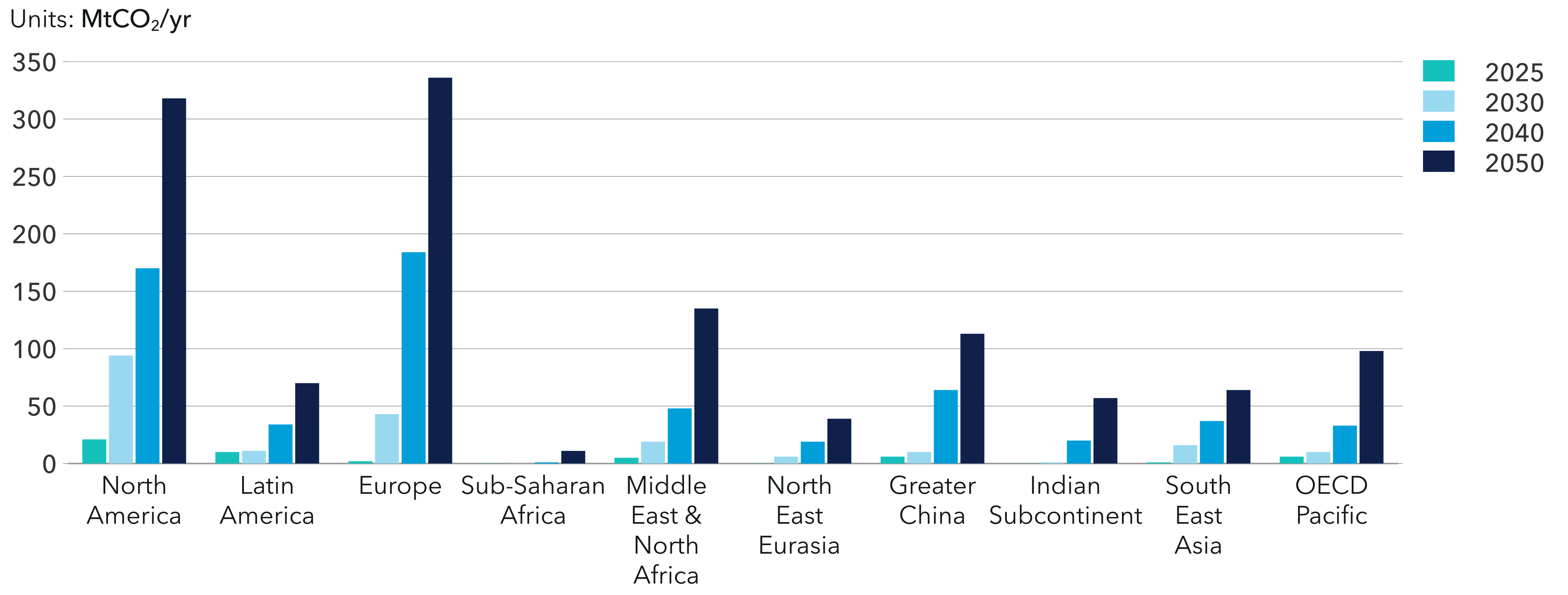


FIGURE 5.9

Regional carbon capture and storage



Onshore storage tanks. Photo: Ruben Soltvedt / Northern Lights.

Although the future of IRA support for CCS in the US is uncertain, CCS has historically advanced there due to the business case for EOR. As a result, DNV's *Energy Transition Outlook* still forecasts North America to account for a quarter of global CCS by mid-century.

The development of CCS in North America and other regions serves to bring the costs of CO_2 capture technologies down through learning-by-doing. Similarly, the experience and learning garnered in transport and storage of CO_2 is transferable to the rest of the regions, albeit to a lesser extent.

In the 2030s, we expect CCS adoption to accelerate in three regions beyond North America: Europe, the Middle East and North Africa, and Greater China. As of 2025, CCS deployment in these regions is at similar levels, ranging from 1.5 to 5.5 $MtCO_2$/yr.

From 2028, we project growth in BECCS for power generation to drive a sharp increase in CCS in Europe, reaching 184 $MtCO_2$/yr by 2040. In contrast, CCS growth in the Middle East and North Africa will remain modest until after 2035 when steam methane reforming (SMR) coupled with CCS production scales up, reaching 45 $MtCO_2$/yr by 2040. We expect Greater China to see a surge beginning around 2030, reaching 64 $MtCO_2$/yr by 2040.

We project all three regions will achieve 30 to 100 $MtCO_2$/yr captured and stored by the second half of the 2030s, though driven by distinct regional priorities and motivations (Figure 5.10).

In Europe, the primary driver for CCS adoption is the continent's carbon neutrality target and its ambitious decarbonization agenda – particularly in the power sector and hard-to-decarbonize industries like cement. The EU carbon price plays a key role by narrowing the cost gap for carbon capture and storage, making CCS increasingly competitive.

From 2030 onward, we expect CCS in cement production to scale significantly. By 2040, nearly 75% of all captured CO_2 in Europe will come from power generation and cement, with 15% of power sector emissions being captured. By 2050, we forecast Europe will capture and store 336 $MtCO_2$/yr through CCS.

The biggest challenges to the widespread adoption of CCS in Europe are:

– Regulatory uncertainty, especially national regulatory frameworks differing when it comes to transnational infrastructure projects

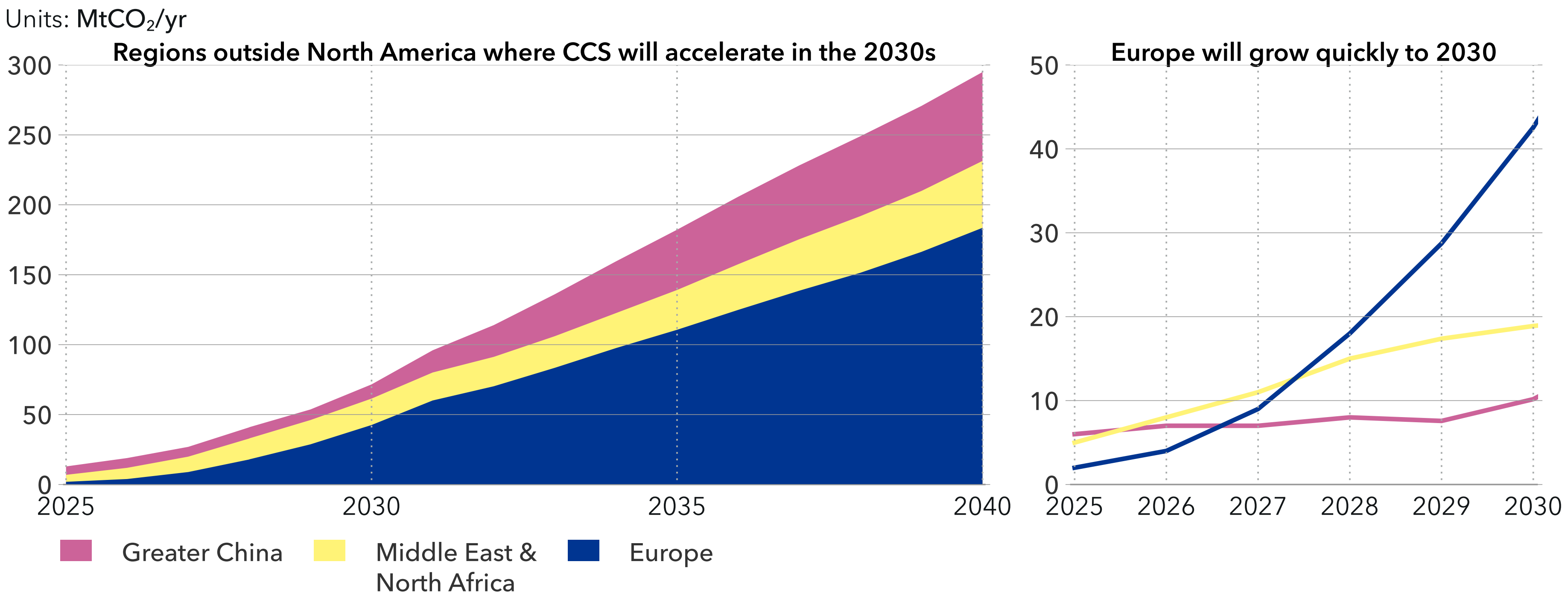
– Initial high costs with respect to high public and private investments needed

– The necessity of establishing new infrastructure, such as offshore pipelines and storage

– Lack of public acceptance, especially as a roadblock to establishing infrastructure

FIGURE 5.10

CCS uptake in selected regions



Despite these challenges, we think Europe will adopt CCS because of three factors:

– Clear business case: The economics of CCS are increasingly favourable in Europe, particularly as carbon prices rise and incentives for low-carbon technologies strengthen. This creates a compelling business case for industries to invest in CCS as a cost-effective strategy for maintaining compliance and competitiveness.

– High decarbonization pressure: Europe faces some of the most stringent climate targets globally, with net-zero goals and sector-specific emission reduction obligations driving urgent demand for deep decarbonization solutions – especially in hard-to-decarbonize sectors where CCS is one of the few viable options.

– Improving public awareness: Public awareness of the role of CCS is gradually improving, aided by greater understanding of climate challenges and stronger government leadership. Germany, for example, is actively developing CCS policy frameworks and has seen a notable shift in public sentiment, creating a more supportive environment for deployment (DNV, 2025).

Trade as a motivator for CCS

By 2040 in the Middle East and North Africa, carbon prices will still be relatively low when compared with the cost of CCS. But the region's ambition to extract domestic natural gas and sell derived commodities and future energy carriers (natural gas in the medium term and hydrogen and ammonia in the long term) to Europe, their most important market, is the biggest motivator to begin adopting CCS at scale for natural gas processing, methane-based hydrogen production, and ammonia production. By 2040, we forecast that the Middle East and North Africa will capture about 48 MtCO_2/yr, about half of which will be from these applications.

There are some other key factors which enable the rapid deployment of CCS in the Middle East and North Africa (Lockwood and Azadegan, 2023):

– Their extensive fossil fuel resources provide strategic storage sites and transportation infrastructure

– Most oil and gas activities are organized through vertically integrated national oil companies, which also aid in infrastructure investment and access to capital

– Clustering industrial and fossil fuel hubs provides the necessary economies of scale for the deployment of CCS

Abate or perish

Greater China's dual carbon goals, to reach peak emissions by 2030 and carbon neutrality by 2060, are an important driver of CCS deployment in the long term, especially in the power and industrial sectors. Similarly, the expansion of the Emissions Trading System (ETS) to include cement, steel, and aluminium in 2025 also provides greater impetus

We expect CCS to play a limited role in Greater China compared to electro-technologies; serving as a tool to meet long-term net-zero targets.

and support for the adoption of CCS towards 2050, while coal-fired power coming under the ETS reduces the relative cost of CCS for coal-fired power (Energynews, 2024).

Despite its leadership in other clean technologies, Greater China has been slower to adopt CCS. However, by 2040, it is projected to capture 64 $MtCO_2$/yr, increasing to 113 $MtCO_2$/yr by mid-century.

This relatively low CCS uptake should be viewed in context. Greater China's technological focus is centred on electro-technologies – such as solar PV, batteries, and electric vehicles – which not only reinforce its industrial competitiveness but also support national energy security goals. In contrast, we expect CCS will play a more limited role, primarily serving as a tool to help meet long-term net-zero targets from the 2040s onward, rather than being a core pillar of the country's clean technology strategy.

We expect Greater China to scale CCS deployment mainly for the following reasons (Wang et al., 2023):

- Increasing technological cooperation with international market players, especially along the entire CCS technological value chain of capture, transport, and storage
- Utilizing public investment opportunities, especially with state actors such as state grid corporations and power utilities
- Provincial and central governments investing in CCS as a means to increase competitiveness

In the longer term, beyond 2040, the need to preserve the competitiveness of their commodities among their key markets – which will continue to enact anti-carbon leakage mechanisms, such as the EU's Carbon Border Adjustment Mechanism (CBAM) – also leads to Greater China adopting CCS in its manufacturing sectors, such as steel production and chemicals production. By 2050, CCS in steel production will account for 21 $MtCO_2$ /yr, or about a fifth of Greater China's total CCS.

Towards 2050, we expect similar dynamics to play out in the OECD Pacific region, with a rising carbon price driving the deployment of CCS in cement and steel production. We forecast that OECD Pacific will have CCS of 98 $MtCO_2$/yr in 2050, of which cement and steel production combined will account for more than half.

CCS by 2050 – growing but not fast enough

By 2050, we foresee most regions having deployed CCS at scale, mostly due to cost reductions from adoption in the previous decades. We project the Indian Subcontinent, Latin America, and South East Asia to each capture between 40 and 60 $MtCO_2$/yr in the 2040s (Figure 5.9), driven by increasing carbon prices, the decreasing cost of CCS, and the need to abate to be able to trade with the rest of the world.

While the absolute values of CCS in each region give us a sense of scale, it is also important to understand how much CCS contributes to avoiding emissions in each region. By 2050, we expect Europe to capture 31% of its emissions through CCS, and North America 26% of its emissions (Table 5.2). The Indian Subcontinent and Greater China, the two regions with the highest emissions, will likely capture only 1% and 3% of their emissions, respectively. Overall, we predict CCS to capture about 6% of the world's emissions by 2050. Thus, we expect CCS to grow, but not fast enough to meet anticipated decarbonization needs.

TABLE 5.2
Percentages of emissions captured by CCS

Regions	2030	2040	2050
NAM	3%	10%	26%
LAM	1%	3%	6%
EUR	1%	13%	31%
SSA	0%	0%	1%
MEA	1%	2%	6%
NEE	0%	1%	2%
CHN	0%	1%	3%
IND	0%	0%	1%
SEA	1%	2%	4%
OPA	1%	4%	18%

5.5 IMPLICATIONS FOR EMISSIONS

The world is far from on track to meet the *Paris Agreement* goals to limit global temperature rise to well below 2°C and achieve climate neutrality in the second half of the century. The global effort to reduce fossil fuel use is the greatest contribution to reducing global emissions, but it is not enough. Reaching climate neutrality will require additional effort to capture or remove CO_2 and safely store it.

More energy, fewer emissions

In 2024, global emissions were 38 $GtCO_2$/yr (Figure 5.11). The growth of the global economy and population through 2050 would further increase the energy-related emissions by 58% to 59 $GtCO_2$/yr if emissions were to grow in line with final energy demand and there were no changes in carbon intensity. Various improvements – such as efficiency through advanced machinery, improved processes, and replacing fossil with renewable electricity – will reduce these predicted emissions by 63%. The emissions that are not abated will need to be captured, either at the point of release or later removed from the atmosphere.

In 2050, annual emissions will still be 22 $GtCO_2$/yr (Figure 5.12) after emission reductions. Some of these emissions – such as in the buildings and power sectors and road transport by passenger vehicles – are not that hard to decarbonize, but they will take time to abate everywhere economically. Others – such as process emissions in manufacturing and emissions from ships – are hard to decarbonize by other means, but could be captured at the emission source. Finally, there are also emissions that are hard to decarbonize and hard to capture, such as those from aviation.

Insufficient carbon capture and storage

In 2024, CCS, including related forms of CDR, addressed 0.1% of global CO_2 emissions. Although this will grow significantly to 6% of emissions in 2050 (1.3 $GtCO_2$/yr), it is still much less than needed to limit warming to 1.5°C. The latest DNV scenario for a challenging pathway to this temperature goal requires 8 $GtCO_2$/yr combined carbon capture and removal in 2050, followed by net removal beyond 2050 (DNV, 2023b).

After the various steps to abate emissions, CCS with capture at the emission source is the next easiest option to reduce emissions (for details, see Section 2.1). However, in 2050, only 1 $GtCO_2$/yr, or 4.5% of the remaining emissions will be captured this way (Figure 5.11). CCS is limited by three factors:

- Not all emissions are sufficiently localized for CCS
- It is not economic to capture 100% of CO_2 produced at a site
- CCS will most likely not be deployed everywhere and in every sector it could be. If it were, it would capture 13 $GtCO_2$/yr, or 58% of the remaining emissions in 2050.

The last option for managing emissions that are not abated or captured at the source is to remove them from the atmosphere. BECCS is the simplest approach, in which one grows biomass, which absorbs CO_2 from the air as it grows, before using it as a fuel and capturing the emissions as in CCS. We estimate that 0.24 $GtCO_2$/yr, or 1.1% of the remaining emissions, will be removed by BECCS. BECCS may be able to scale further, but we must ensure that feedstocks are sustainable and we give considerations to biodiversity as we do so.

The amount of CO_2 that will be captured by CCS and BECCS in the different sectors is indicated by the lighter areas in Figure 5.12. This is much less than the maximum amount, which has technical and practical limits including non-localized emissions, incomplete capture rate, and limited use of biomass compared to fossil fuels.

To achieve net-zero, the world needs DAC. DAC is easily scalable and not limited by where the CO_2 is emitted. It is currently the most expensive option, but we expect the price to drop (for details, see the factbox in Section 2.1). However, in 2050, we predict that only 0.08 $GtCO_2$/yr, 0.4% of the remaining emissions, will be removed by DAC, in part due to its high cost that will limit demand. Nevertheless, DAC may play a necessary role beyond 2050 to remove previously emitted CO_2 so the world can recover after overshooting the 1.5°C target (DNV, 2023b).

FIGURE 5.11

Change in CO_2 emissions to 2050

Units: $GtCO_2$/yr

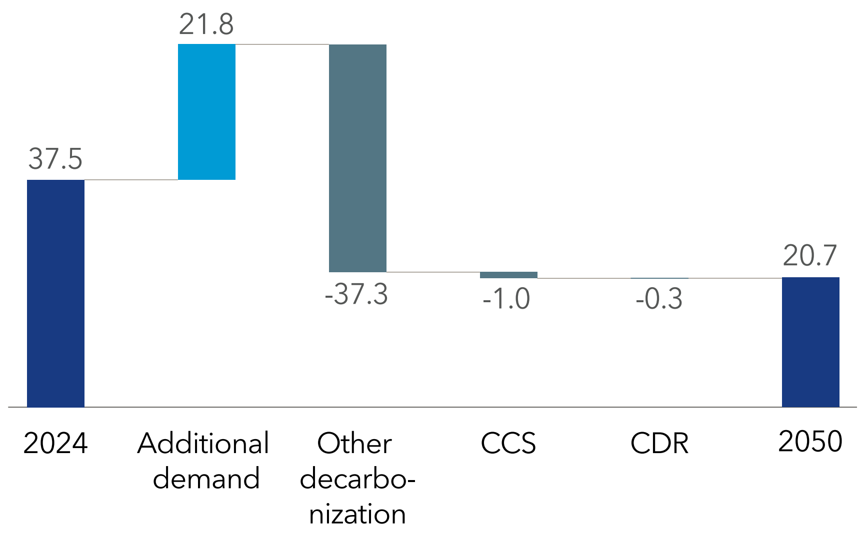
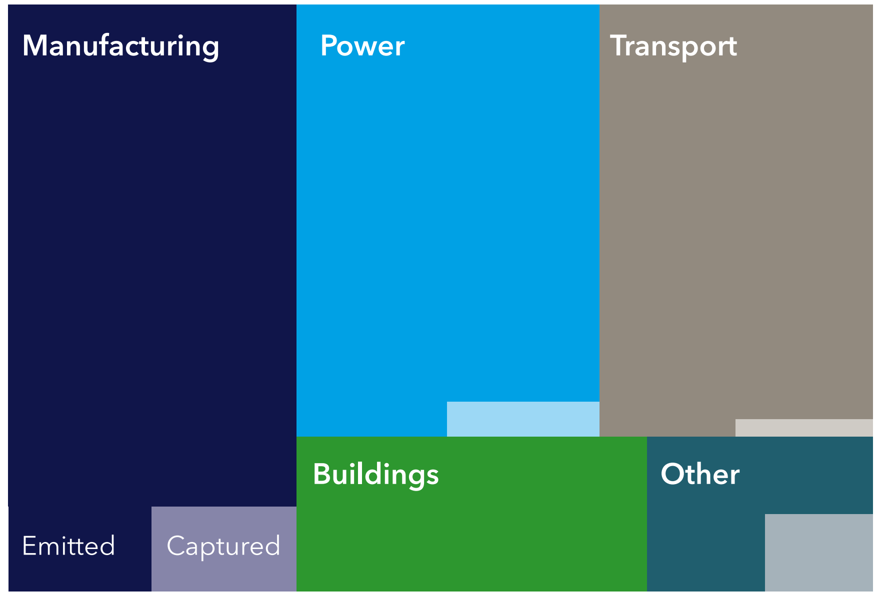


FIGURE 5.12

Emitted vs captured CO_2 emissions in 2050 by sector



The lighter area in each sector indicates how much CO_2 is captured

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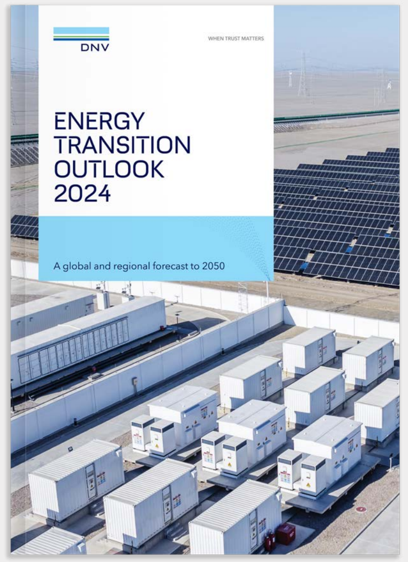

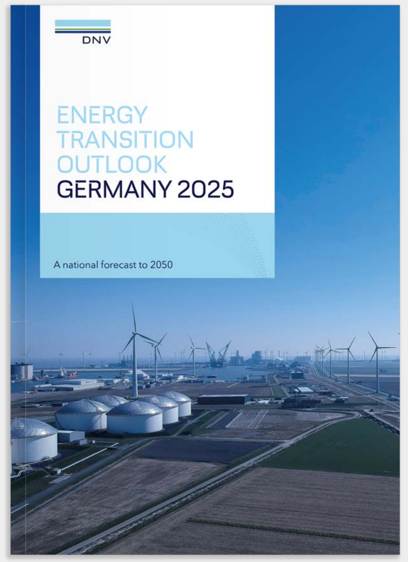

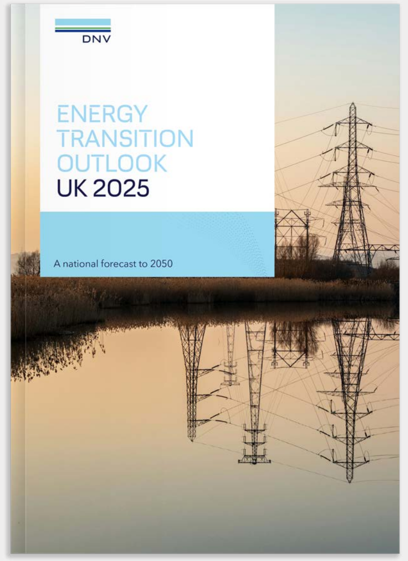

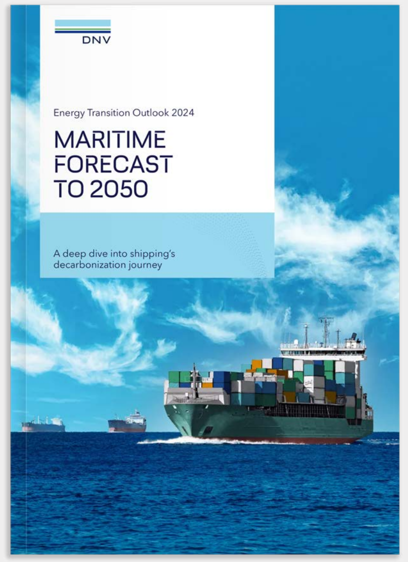

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