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.

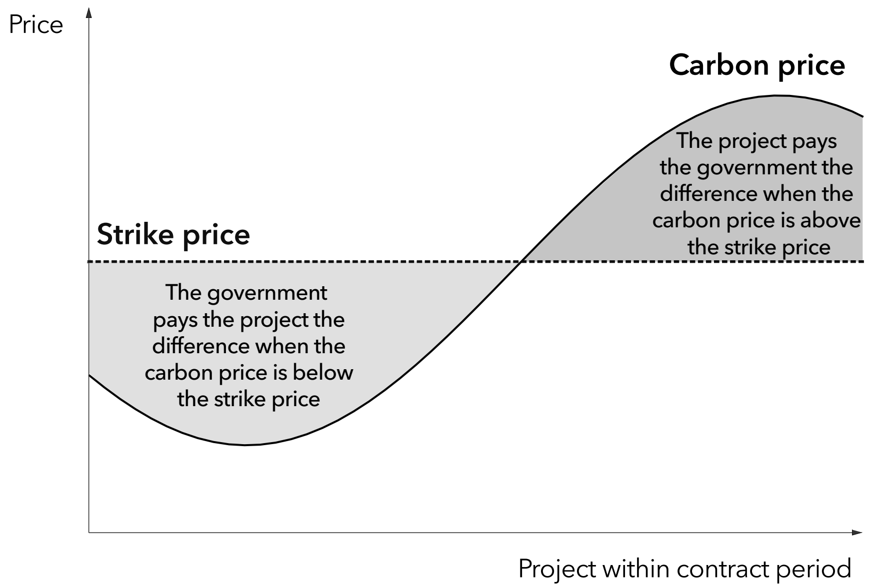
Europe

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.

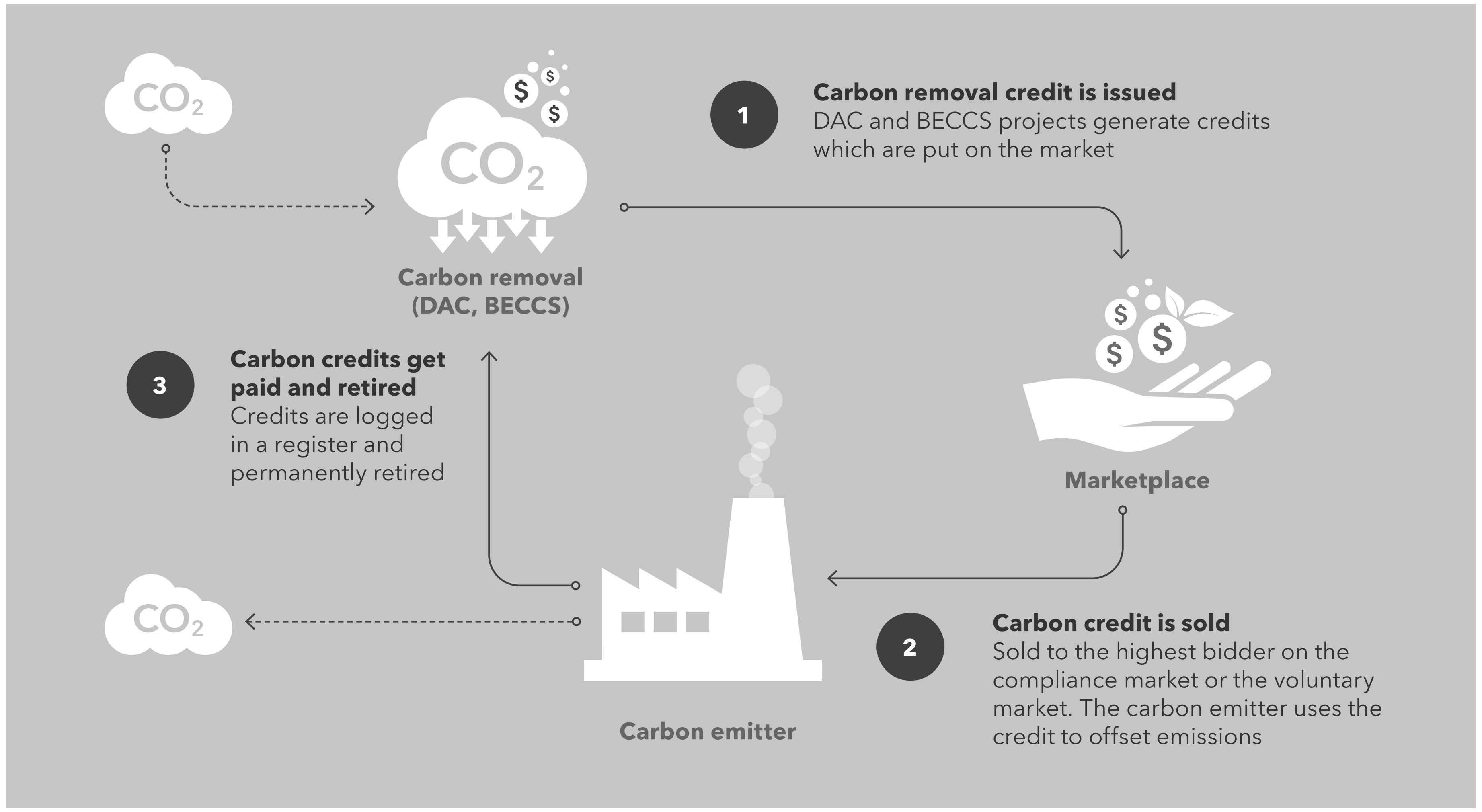
4.4 HOW CARBON MARKETS DRIVE CARBON DIOXIDE REMOVAL

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.

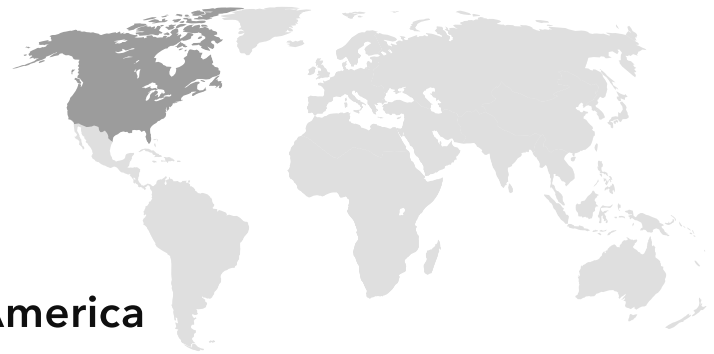
One important international agreement for cross-border CO_2 transport is the *London Protocol* (IMO, 2006). Administered by the International Maritime Organization (IMO), the main goal of the Protocol is to keep the seas clean by stopping pollution from waste dumped in the ocean. Currently, CO_2 is characterized 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.

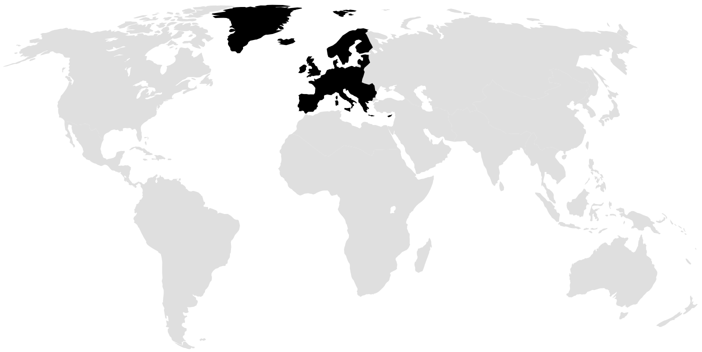
investors. The project is on track to begin operation in 2027 and signals growing confidence in long-term carbon transport and storage solutions.

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.

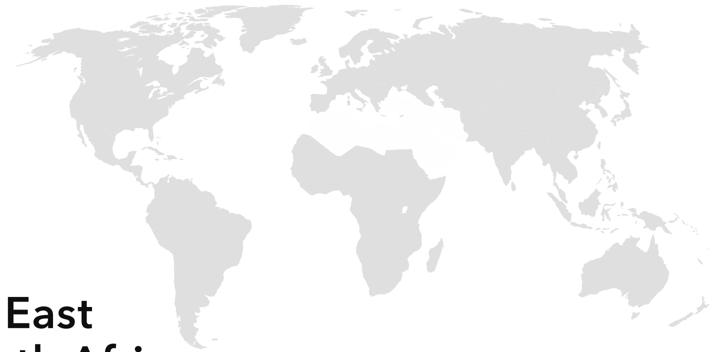
Interest in CDR projects, particularly BECCS, is growing in Europe. Sweden and Denmark have launched specific subsidy schemes that target negative emissions, and many projects have sought to sell credits in the voluntary carbon market. These include Ørsted's bioenergy thermal power plants, Hafslund Oslo 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.

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



Middle East and North Africa

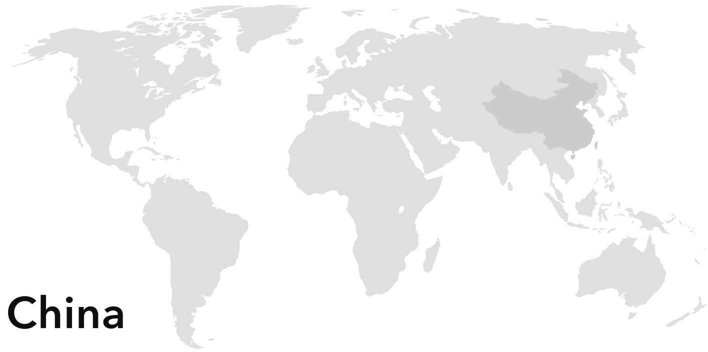
The region has significant CCS ambition, with three operational CCS projects and six under construction. Operating facilities include the Al Reyadah steel plant in the UAE, Qatar's Ras Laffan LNG Facility, and Saudi Arabia's Uthmaniyah gas processing plant. The world's largest CO_2 utilization facility, 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.

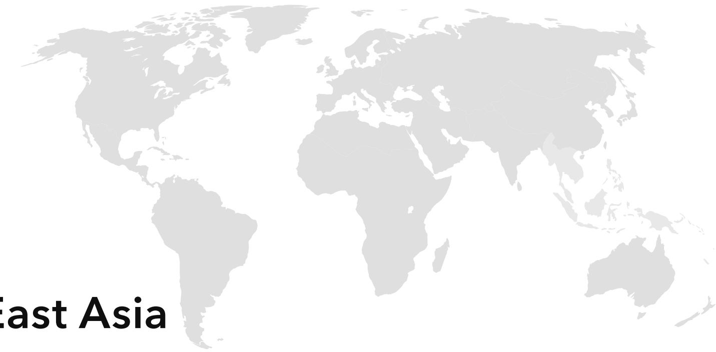


Greater China

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

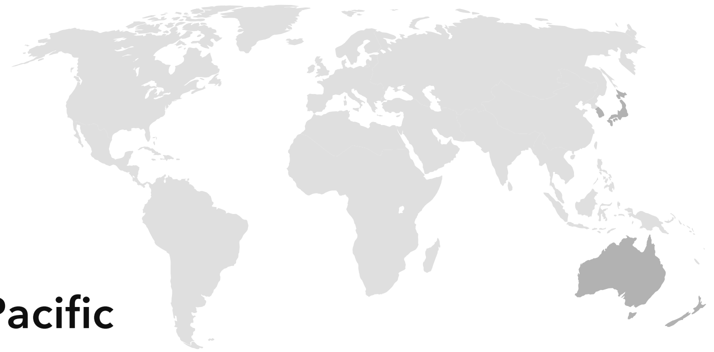


South East Asia

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.



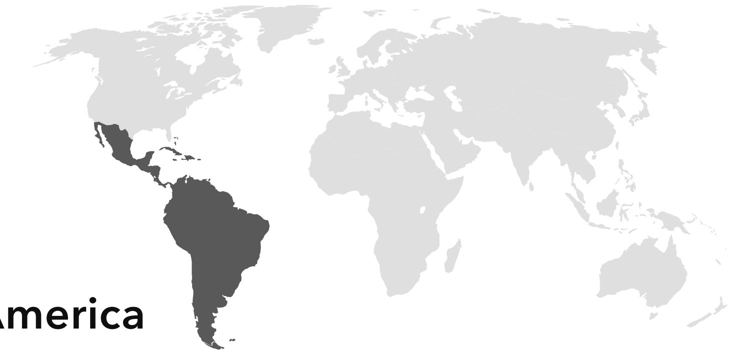
OECD Pacific

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.

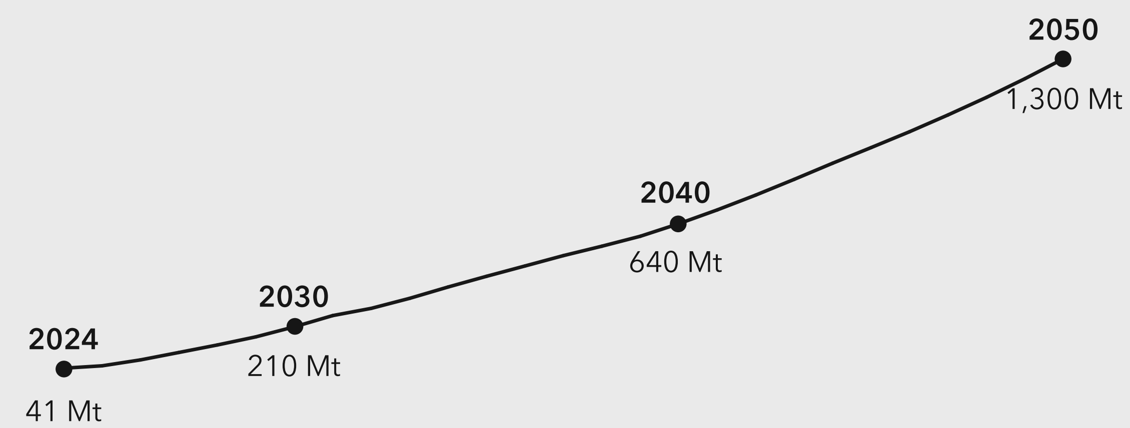
We expect policy-driven growth in CCS capacity to **lower costs by about 14% by 2030**, mainly due to reductions in capital costs for capture technologies and in transport and storage costs.

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)

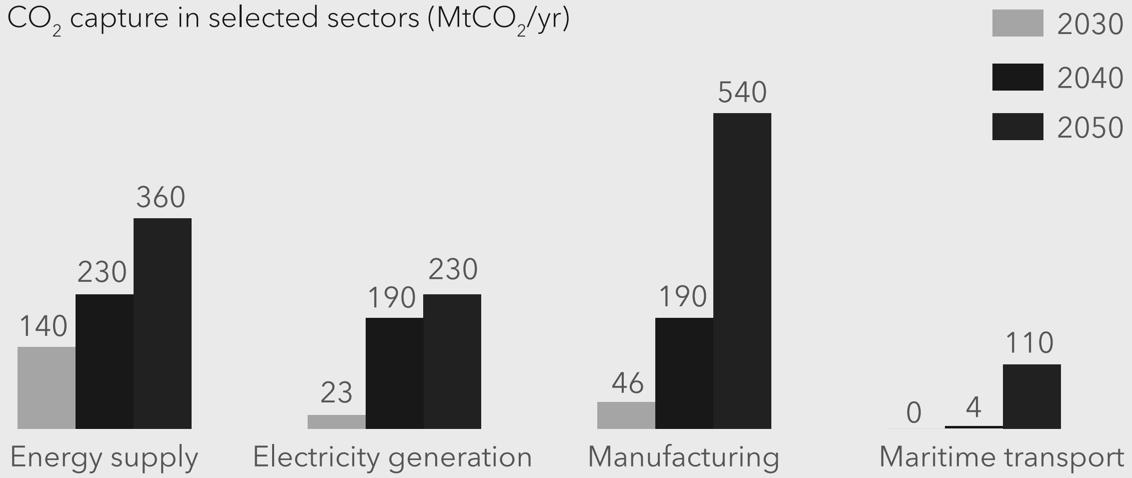


Europe and North America lead uptake

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, renew-ables, 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

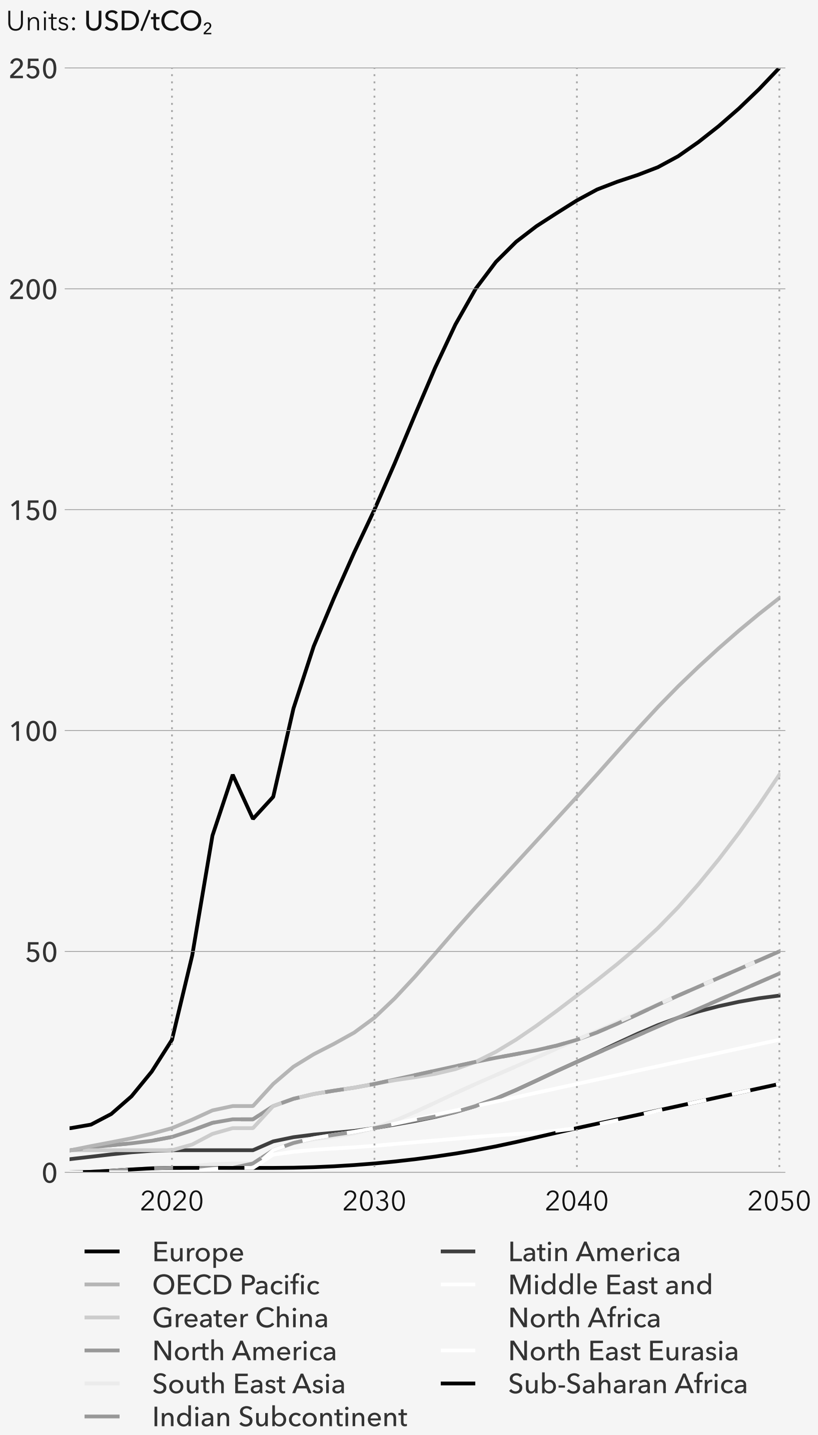


TABLE 5.1

Details on policy factors driving CCS uptake in the ETO model

Carbon capture and storage & direct air capture support	**Carbon pricing schemes**	**Hydrogen 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.	– **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.	– **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.

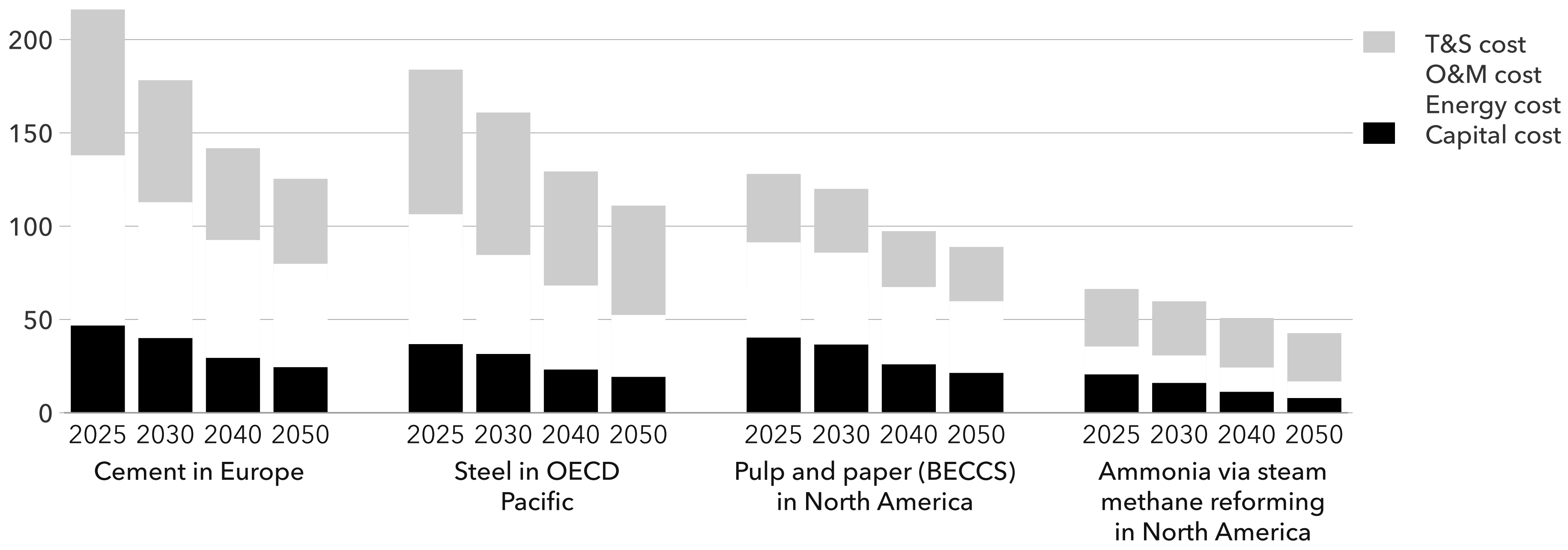
CCS costs also vary significantly by region, largely driven by differences in energy prices and T&S methods and cost components.

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

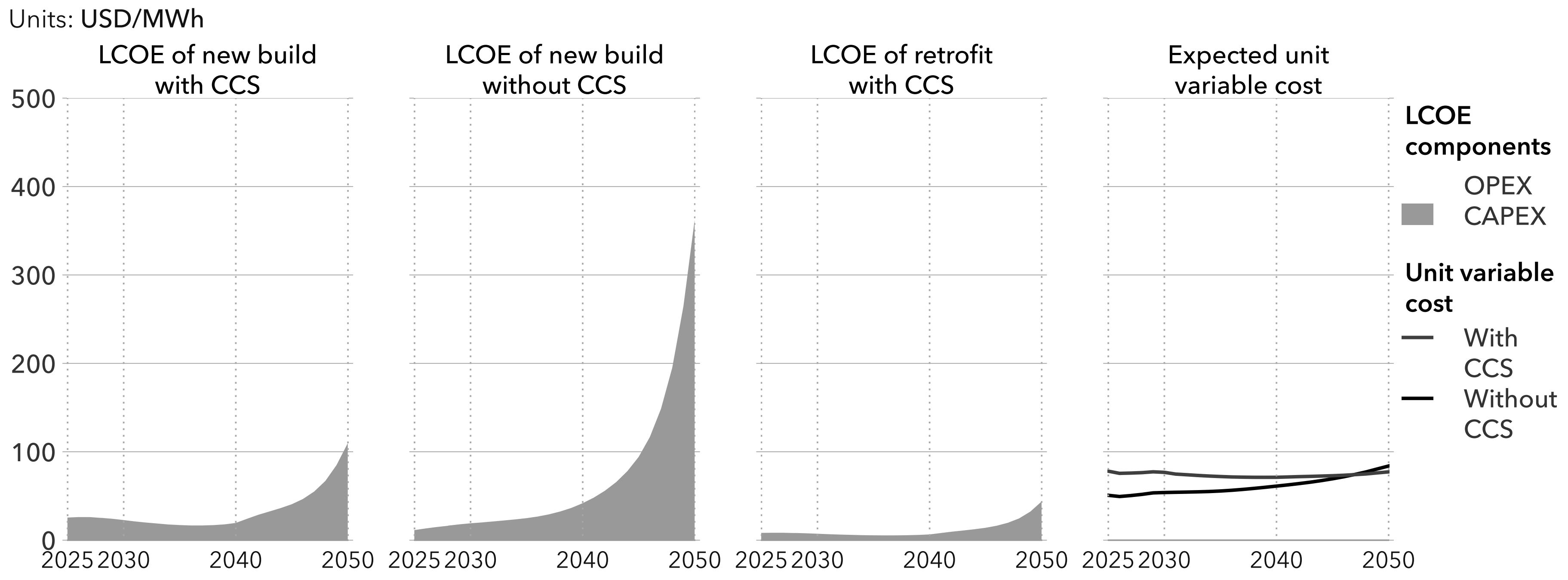
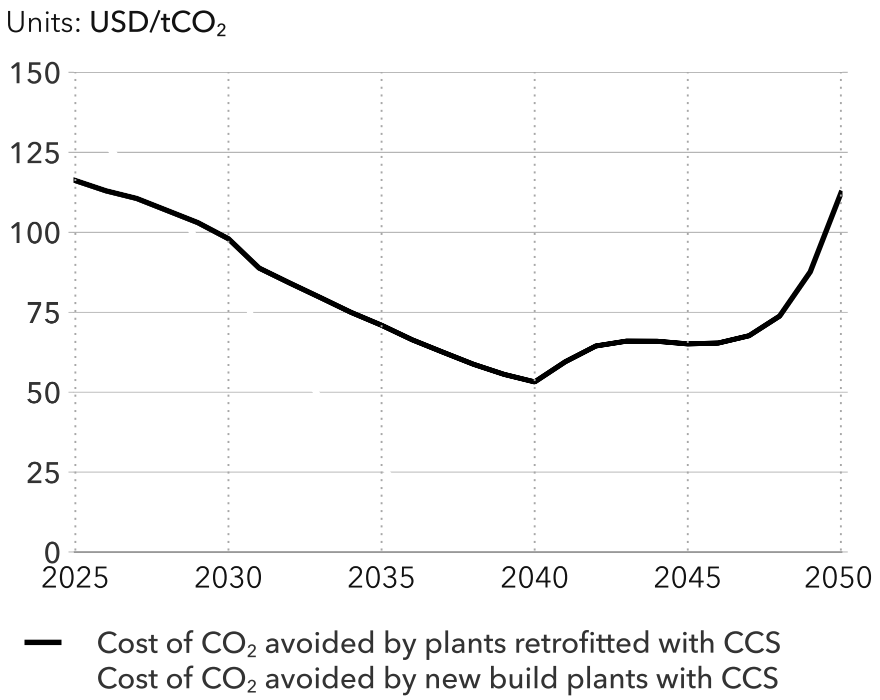


FIGURE 5.4

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.

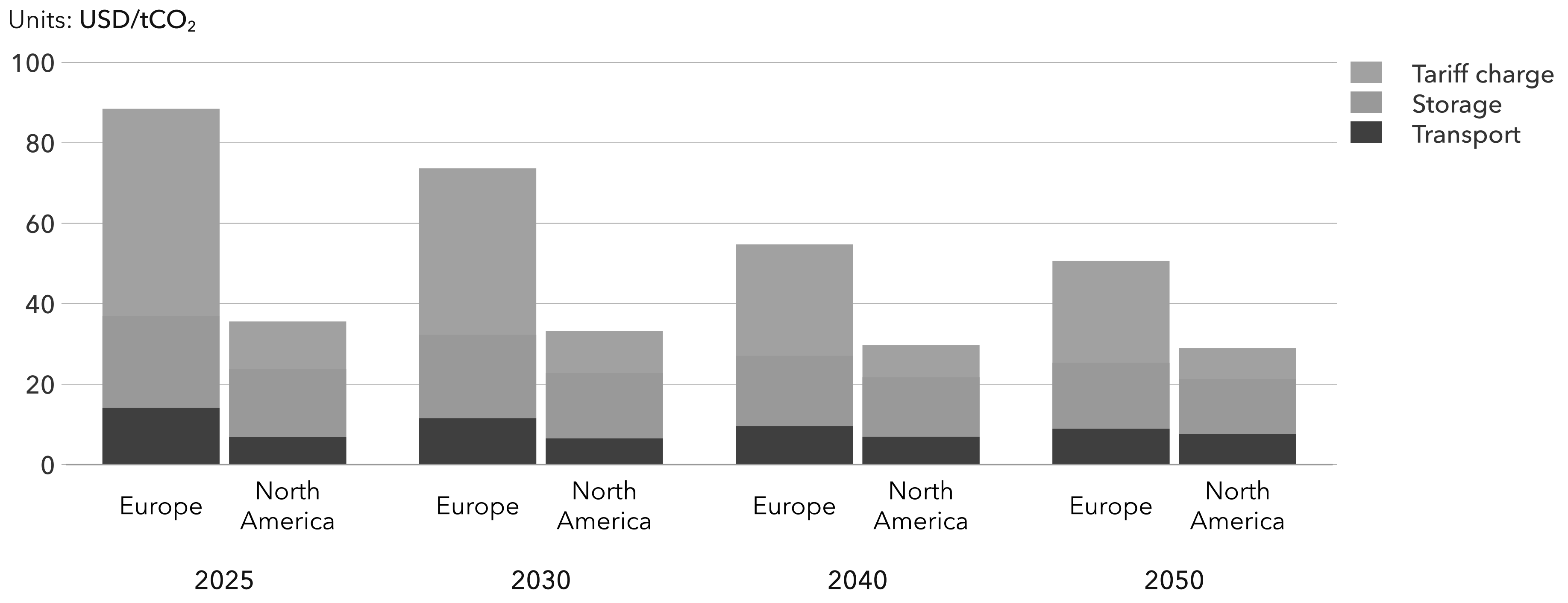
Currently, in North America, the T&S tariff charge comprises about 33% of the total T&S cost, reflecting the more established industry and infrastructure. In contrast, Europe's tariff makes up about 58% of total T&S cost, due to higher risks and early-stage inefficiencies tied to offshore storage and 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



5.2 UPTAKE BY SECTOR

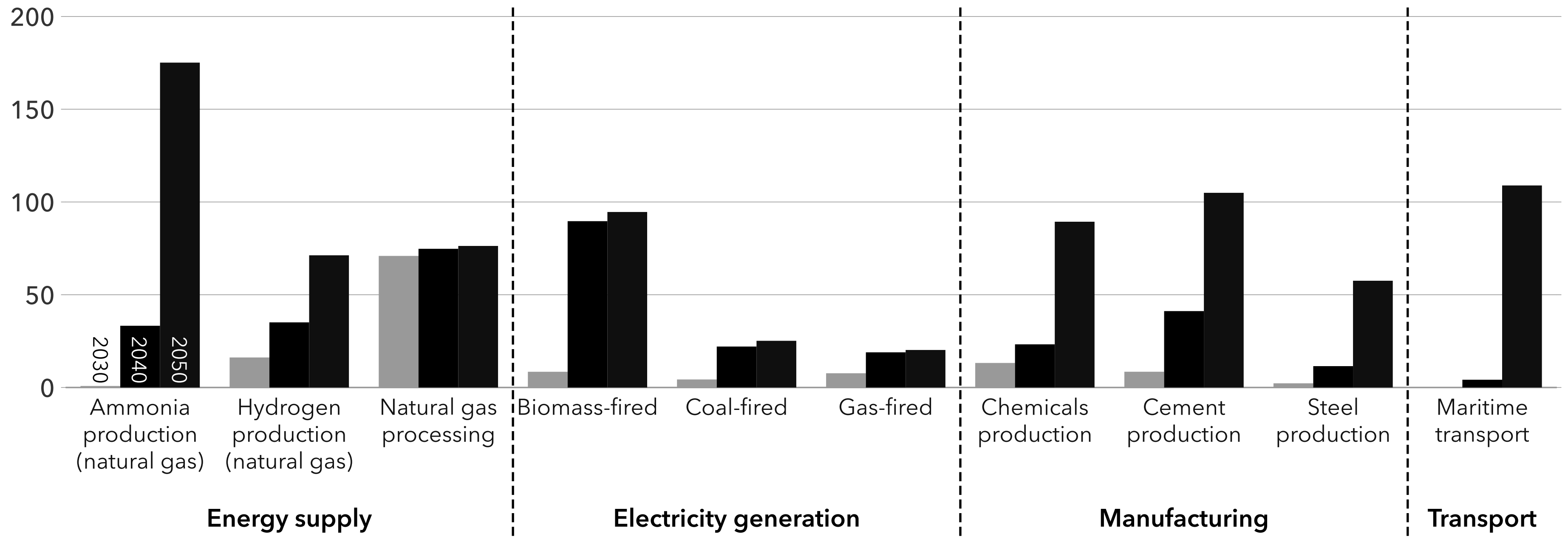
By 2050, we expect 1.3 GtCO_2/yr will be captured and stored – a more than 30-fold increase from the current volumes. However, this strong increase is not uniform across sectors; we see some early-moving sectors stagnating while other sectors come on strongly towards the end of this period.

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).

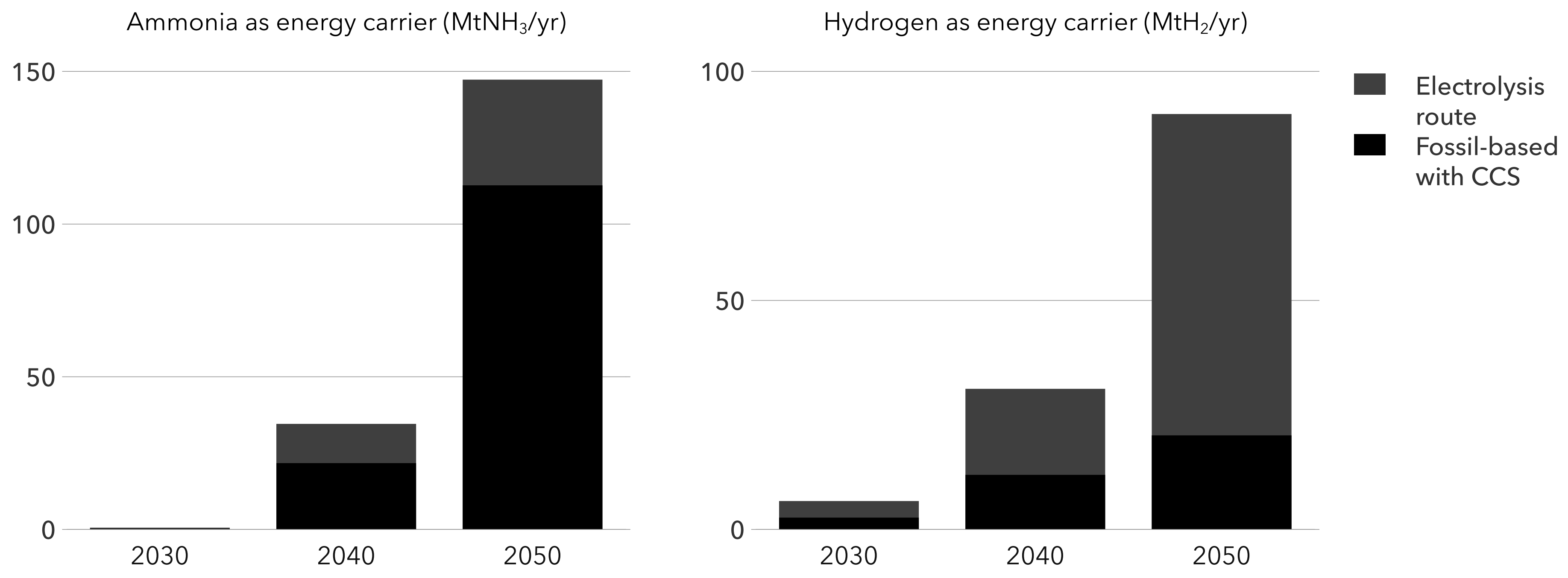
North America is the first mover in this sector because of policy support and existing CCS infrastructure and competence. After moderate sector growth in the first part of the period, the region sees a five-fold growth from 2040 to 2050. North America will lead CCS in ammonia throughout the period to 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.