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 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.

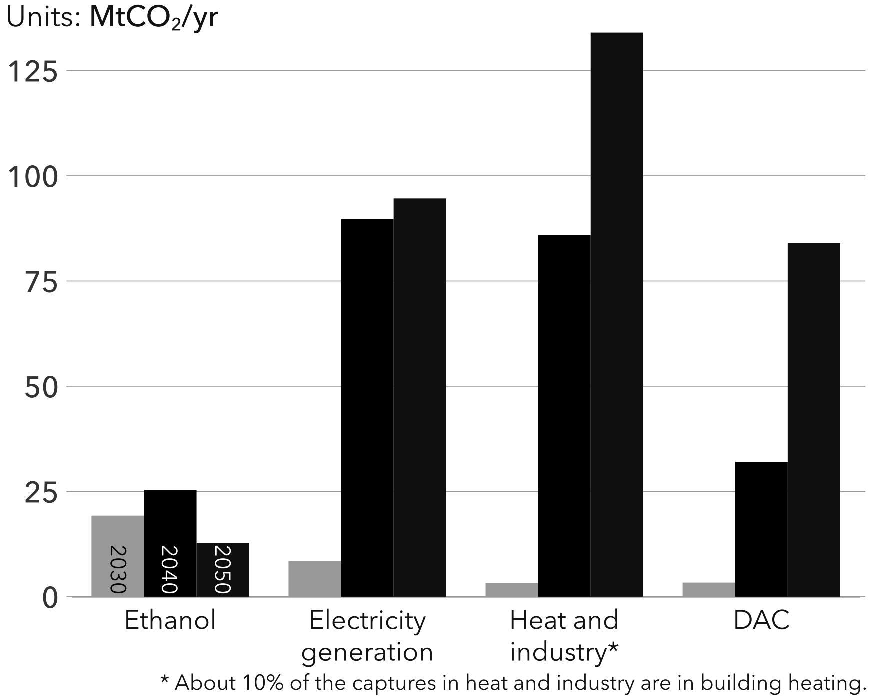
Voluntary demand depends on how many companies or individuals choose to offset their emissions, which in turn depends on the cost; their ability to pay; and, for businesses, the business value of being carbon neutral. This demand is mostly driven by companies with net-zero targets offsetting emissions 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

Units: $MtCO_2$/yr



* 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, infrastructure, 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 experience 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 implementing 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)

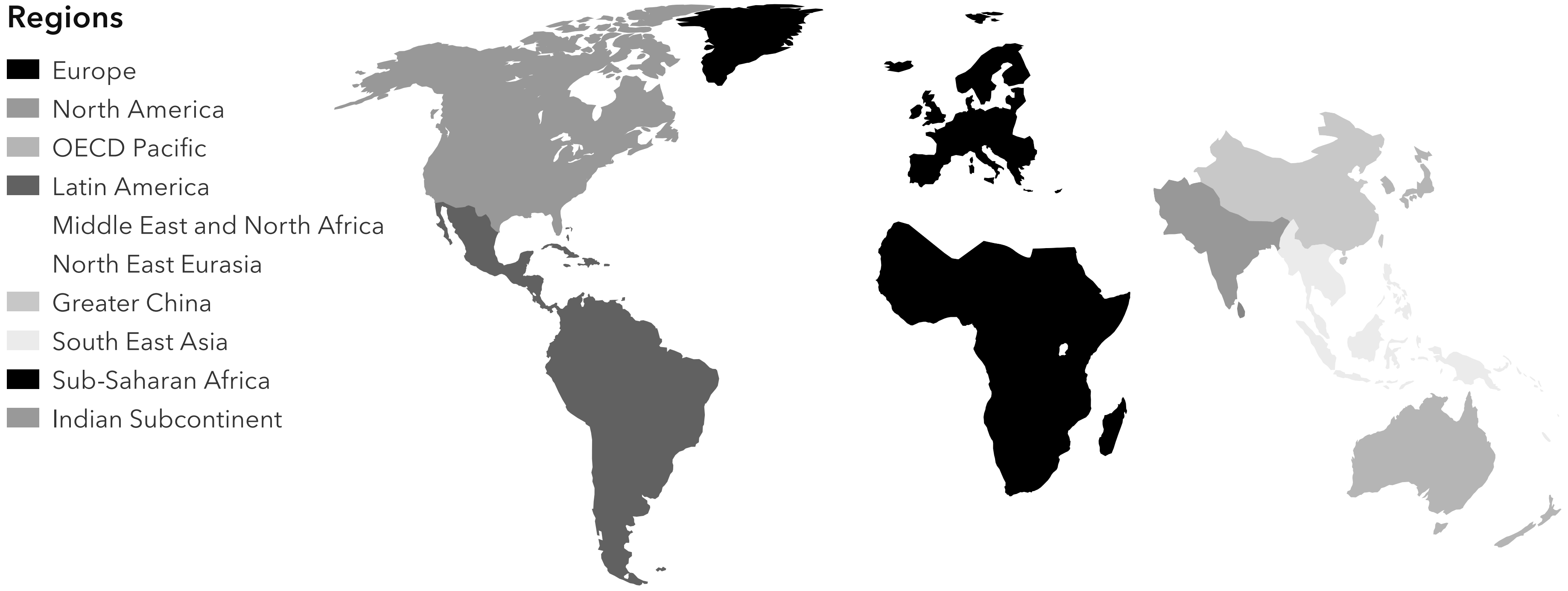
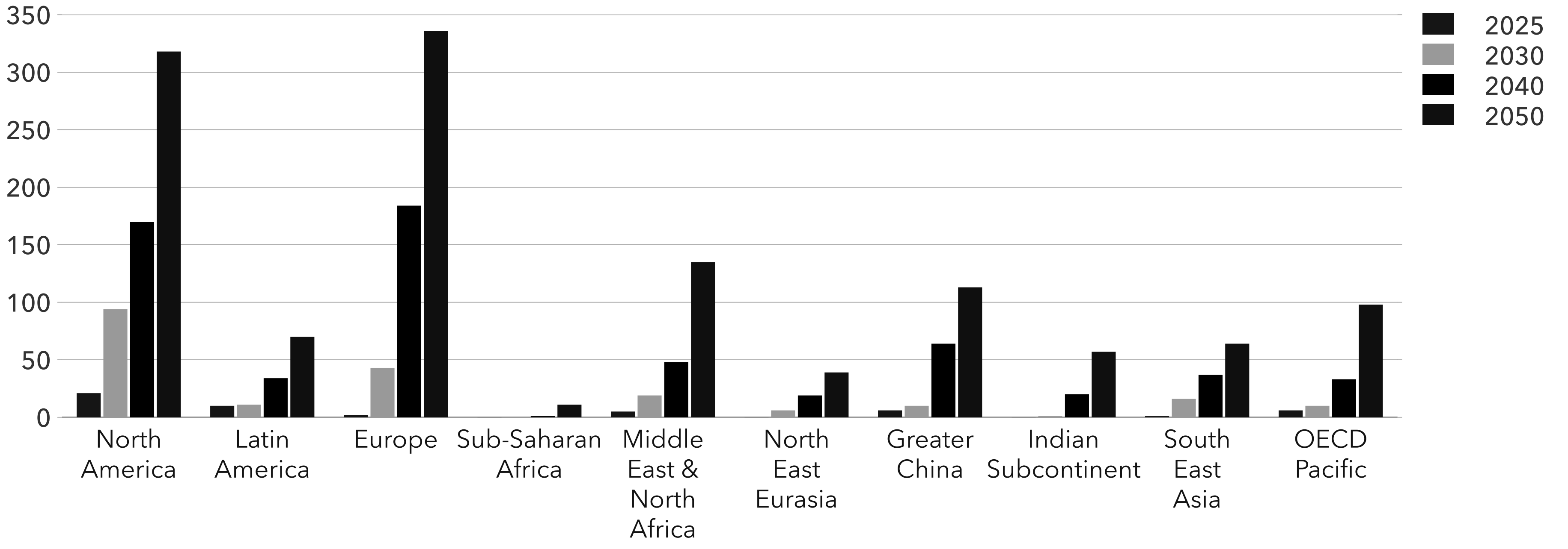
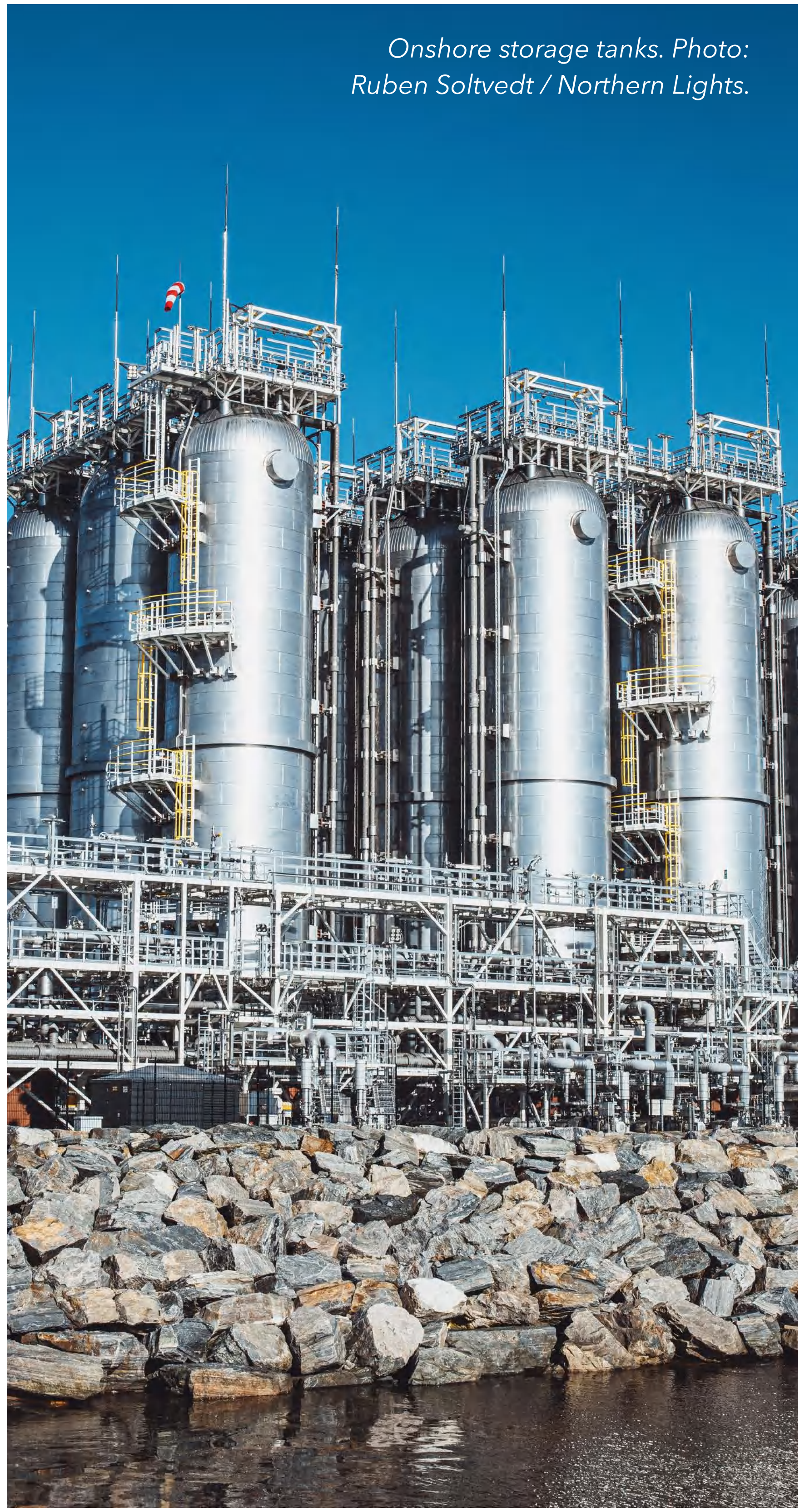


FIGURE 5.9

Regional carbon capture and storage

Units: $MtCO_2/yr$





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.

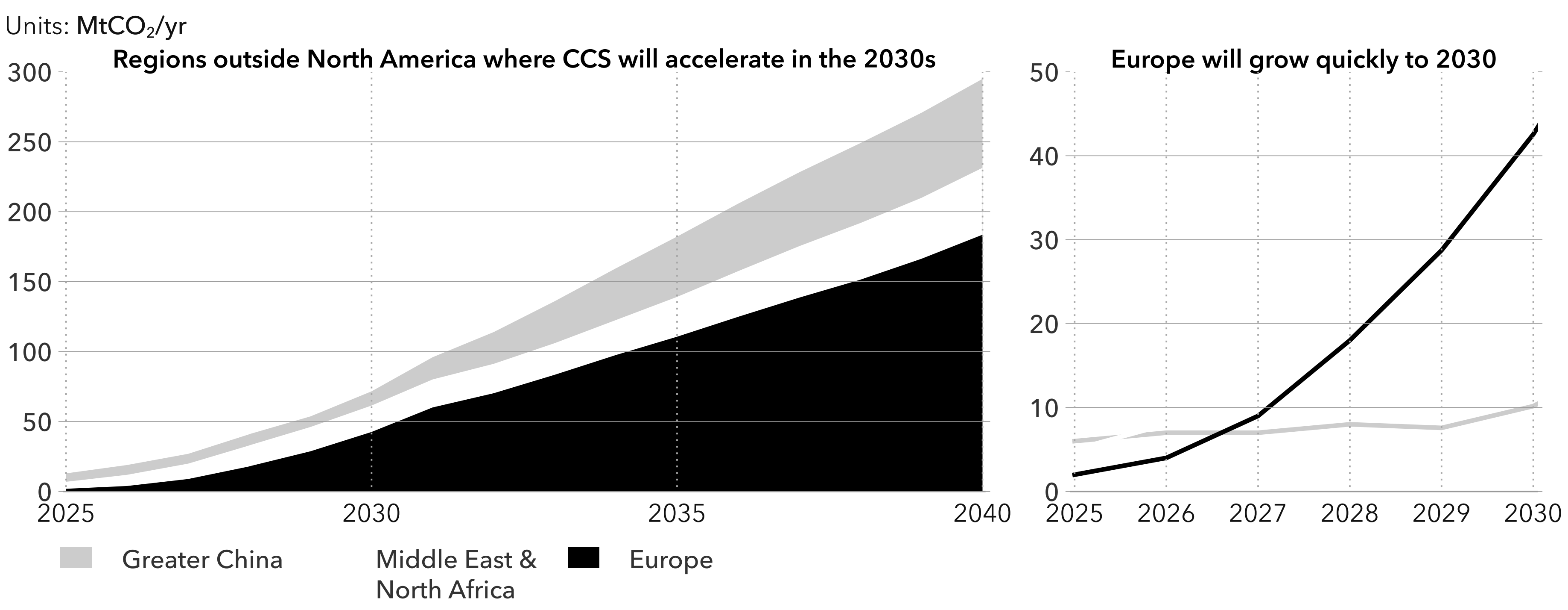
From 2030 onward, we expect CCS in cement production to scale significantly. By 2040, nearly 75% of all captured CO_2 in Europe will come from power generation and cement, with 15% of power sector emissions being captured. By 2050, we forecast Europe will capture and store 336 $MtCO_2$/yr through CCS.

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

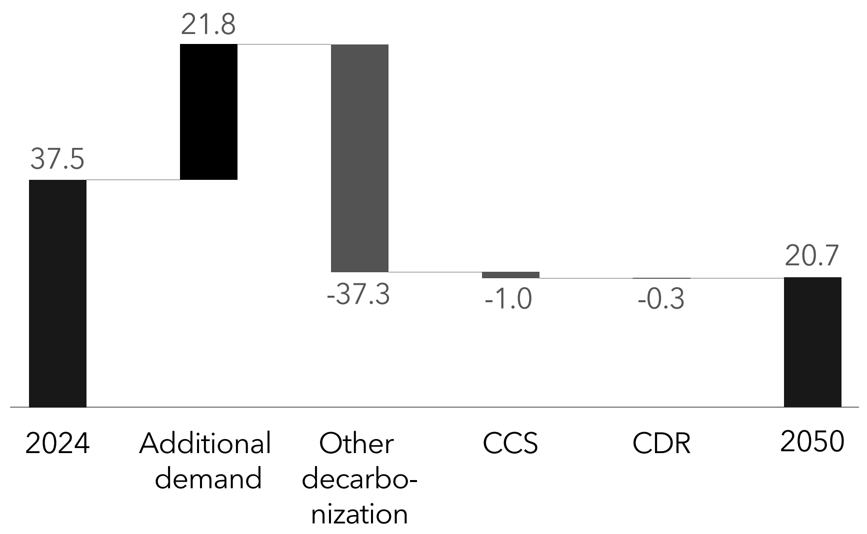
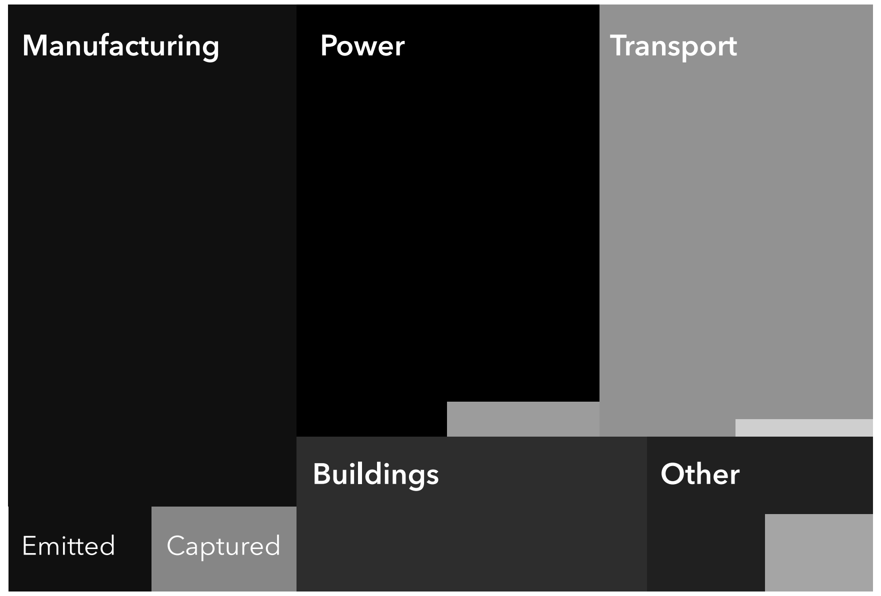


FIGURE 5.12

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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