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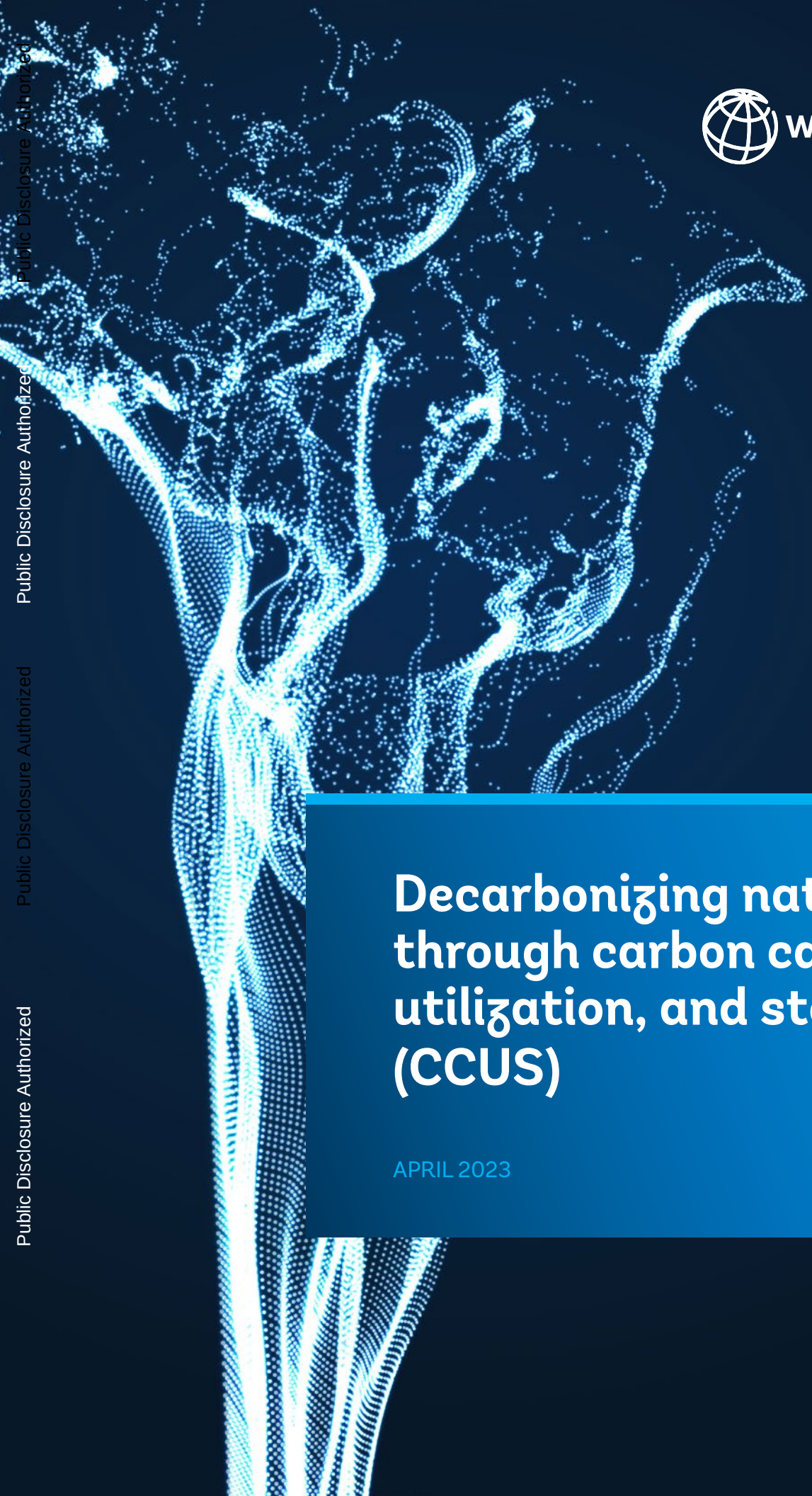

# Decarbonizing natural gas through carbon capture, utilization, and storage (CCUS)

APRIL 2023

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The purpose and scope of this study is to assess the role of carbon capture, utilization, and storage technology in the decarbonization of natural gas production and use. Despite due care and diligence in preparing this report, various key parameters may change, impacting the results.

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# List of Abbreviations

| | |
|---|---|
| **BECCS** | Bioenergy with carbon capture and storage |
| **CCS** | Carbon capture and storage |
| **CCUS** | Carbon capture, utilization, and storage |
| **CL** | Clean hydrogen |
| **$CO_2$** | Carbon dioxide |
| **COP26** | 26th United Nations Climate Change Conference |
| **EJ** | Exajoule |
| **EOR** | Enhanced oil recovery |
| **ETS** | Emissions Trading System |
| **GCCSI** | Global Carbon Capture and Storage Institute |
| **GHG** | Greenhouse gas |
| **Gt** | Gigaton |
| **$GtCO_2$** | Gigatons of carbon dioxide |
| **IBRD** | International Bank for Reconstruction and Development |
| **IDA** | International Development Association |
| **IEA** | International Energy Agency |
| **IEAGHG** | IEA Greenhouse Gas R&D Programme |
| **IEA SDS** | IEA's Sustainable Development Scenario |
| **IFC** | International Finance Corporation |
| **INDC** | Intended Nationally Determined Contribution |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IRENA** | International Renewable Energy Agency |
| **Km** | Kilometer |
| **$ktCO_2$** | Kiloton of carbon dioxide |
| **kW** | Kilowatt |
| **LCH** | Low carbon hydrogen |
| **LNG** | Liquefied natural gas |

# List of Abbreviations

| | |
|---|---|
| **MENA** | Middle East and North Africa |
| **MIGA** | Multilateral Investment Guarantee Agency |
| **MMBtu** | Million British thermal unit |
| **Mt** | Million ton |
| **$MtCO_2$** | Million tons of carbon dioxide |
| **NDC** | Nationally determined contribution |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PV** | Photovoltaic |
| **TIAM-Grantham** | Grantham Institute's Times Integrated Assessment Model |
| **UK** | United Kingdom |
| **US** | United States |
| **WeSIM** | Imperial College's Whole-energy System Investment Model |



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# 1 Executive summary

**The need to find solutions to climate change is ever more urgent, with more frequent climate-related extreme weather events like floods, droughts and fires.** These events have exposed millions of people to severe water and food insecurity, especially in Africa, Asia, Latin America, and on Small Islands. The most recent Intergovernmental Panel on Climate Change (IPCC) reports affirm that we still can keep the world below 1.5 degrees Celsius if decisive actions are taken. Countries around the world acknowledged the imperative to act on climate change with the Paris Agreement in 2015, making pledges, embodied in their nationally determined contributions (NDCs). Addressing climate change will require many solutions, nearly all of which already exist today. For example, improvement to energy efficiency, increases in wind and solar power, biofuels from organic waste, carbon capture, utilization and storage (CCUS), clean hydrogen, setting a price on carbon, protecting forests, are all potent ways to reduce the amount of greenhouse gas emissions.

**There is a strong consensus that CCUS will be needed to achieve net zero emissions.** Significant deployment of CCUS is seen in the IPCC 6th Assessment Report as well as in their 2018 Special Report on 1.5°C. The IEA's recent Net Zero Emissions scenario involves CCUS reaching capture rates of around 5 gigatons (Gt) per year in 2050, and the International Renewable Energy Agency (IRENA) report "Reaching Zero with Renewables" sees CCUS contributing 6 percent of annual emissions reductions in 2050, in the most aggressive Deep Decarbonization Perspective scenario.

**CCUS has been deployed at scale for over 25 years across a range of power and industrial applications, but the roll-out of the technology is falling well behind expectations.** 27 large scale projects are operating today, capturing a combined total of over 35 $MtCO_2$ per year, with a further 106 new facilities under development with capacity to capture a further 110 $MtCO_2$ per year. $CO_2$ capture has been deployed at a commercial scale in natural gas production and processing, liquefied natural gas (LNG) production, power generation, hydrogen production, chemical and fertilizer production, biomass processing, and steel production. While the majority of $CO_2$ captured today is used in conjunction with enhanced oil recovery (EOR), most of the new planned projects aim to permanently store $CO_2$ solely for climate change mitigation purposes, much like Norway's Sleipner Project, in operation since 1996. Despite this, the International Energy Agency (IEA) considers CCUS deployment to be "not on track" in both power generation and in industry, as is the case with many climate change mitigation technologies needed to reach net zero.

**Challenges remain with the roll-out of the technology, and CCUS will not be applicable or available in all circumstances.** Although, globally, $CO_2$ storage capacity is considered to be adequate to meet the world's needs at the national and local levels, there is uncertainty over the $CO_2$ storage potential, with $CO_2$ storage exploration and characterization requiring investment and long lead-times. CCUS legal and regulatory frameworks are underdeveloped, particularly in developing and emerging economies. Having a robust legal and regulatory framework is key to ensuring CCUS operational health and management of safety risks and to provide certainty on the long-term stewardship of the stored $CO_2$. CCUS is also a capital-intensive technology with abatement costs ranging from \$15–120/$tCO_2$[1] – higher in many instances than abatement costs from renewable energy or energy efficiency. Public acceptance of CCUS can also be a challenge, with perceptions of technology risks as well as concerns about the perpetuation of fossil fuels. In many instances, CCUS may not be applicable or available, or more affordable alternatives may exist.

**Despite these challenges, if countries continue to produce and use natural gas, as stated in many NDCs, CCUS may be the most economically viable, and in some cases the only, mitigation option available.**

- **CCUS may play a key role in addressing the emissions from natural gas use in some hard-to-abate industries.** Natural gas is a major energy source in industry today, as a fuel for electricity or heat production, as a feedstock for a range of industrial processes including chemical and fertilizer production, and in cement production. Where natural gas is used in industry for electricity, renewable energy, along with battery storage and/or grid connectivity to provide a continuous power supply, is likely to do most of the decarbonization heavy lifting. Where natural gas is used for high-temperature heat or as a chemical feedstock with associated process emissions, CCUS, and in some instances clean hydrogen (CL), are considered to be the most economically viable, and in some cases, the only mitigation option available.

1 \$ sign here and throughout refers to US dollars.

- **In countries where low-cost natural gas is available, deploying CCUS on gas power generation may reduce the costs of fully decarbonizing the electricity grid. Renewable power technologies, such as solar PV and onshore wind, are now the cheapest source of electricity available and so will be central to any decarbonized power grid.** However, wind and solar are variable, with output depending on weather conditions, although battery storage can provide firm and dispatchable capacity to a degree. However, at very high levels of output, renewables require large volumes of supporting battery storage to store a large share of excess output, with increasingly high battery costs. To reduce the costs of maintaining reliable electricity supply, renewables and battery storage may be complemented with alternative sources of firm and dispatchable low-carbon capacity, such as reservoir hydropower or CL. In regions with abundant low-cost natural gas supply, natural gas power generation with CCUS may also be used to provide firm, dispatchable, synchronous low-carbon power to complement large penetrations of variable renewables.
- **While the specific contribution of low-carbon hydrogen to total CL supply is highly uncertain, it is likely to play a valuable role in developing a CL market and is also likely to remain competitive in regions with abundant natural cheap gas.** In the near-term, low-carbon hydrogen is available to be rolled out at scale and at lower cost than renewable hydrogen in countries with significant natural gas resources. While renewable hydrogen is expected to emerge as the main source of clean hydrogen as the technology scales up and its costs decline, low-carbon hydrogen is likely to remain competitive in regions with abundant low-cost gas. In the long-term low-carbon hydrogen can be integrated with direct air $CO_2$ capture and storage (DACCS), utilizing shared $CO_2$ transport and storage infrastructure, to offset residual emissions in the supply chain for fully zero-emission hydrogen, or even negative-emission hydrogen with greater amounts in DACCS.

**If natural gas continues to be used, emissions associated with gas production and supply must be addressed, including through CCUS on natural gas and LNG production.** Reducing fugitive methane emissions and ending routine gas flaring is an essential part of natural gas production and use, supported by initiatives such as the Global Gas Flaring Reduction Partnership. In addition, natural gas is often produced along with $CO_2$ emissions that naturally occur in some reservoirs. This $CO_2$ is commonly separated and vented to the atmosphere, in order for the natural gas to reach either the specifications of regulatory requirements from the natural gas grid or technical requirements for processes such as LNG production. CCUS with gas production and processing is a mature, cost-effective technology, supporting affordable, near-term emissions reductions. At \$15–20/t$CO_2$ it is among the cheapest applications of CCUS, and accounts for 70 percent of total CCUS deployed globally today.

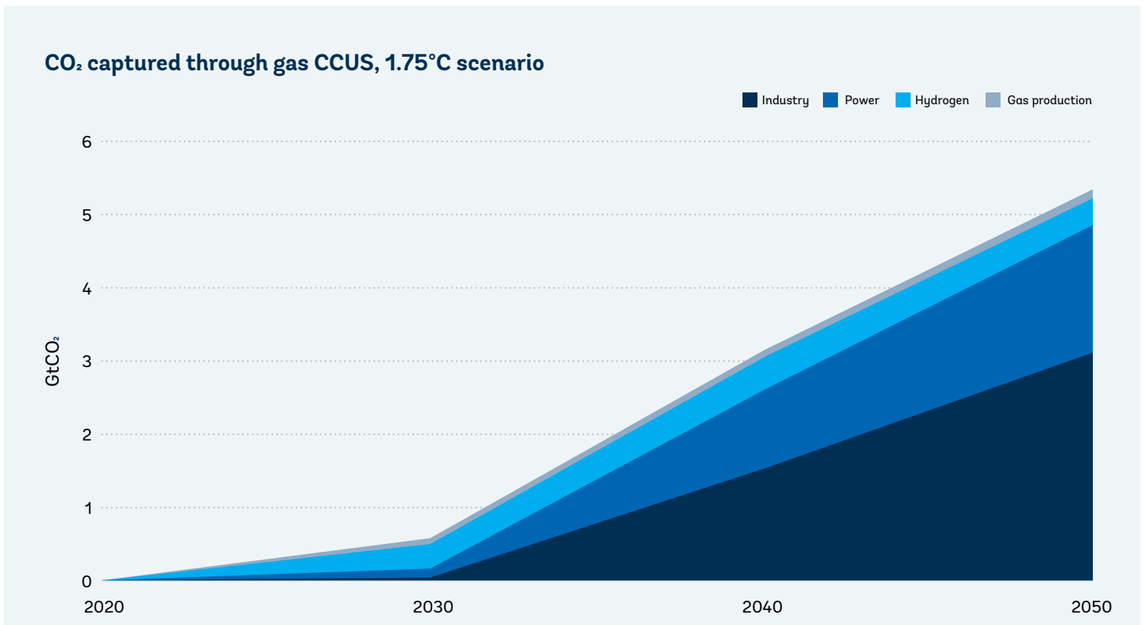
**The present study assesses whether the application of CCUS on natural gas production and use could play a significant role in achieving the objectives of the Paris Agreement,** finding that if countries continue to use natural gas in power generation and in industry, CCUS must be applied in addition to addressing natural gas supply chain emissions.

**Scenario analysis undertaken as part of the study[2] concluded that CCUS applied on natural gas could avoid up to 5 gigatons of carbon dioxide ($GtCO_2$) emissions annually by 2050 in a "well below 2°C" (1.75°C) scenario** (Figure ES.1). The primary application of CCUS on natural gas use is likely to be decarbonizing gas-based heavy industry, followed by power generation, with supplementary applications in CL production and natural gas production. CCUS could potentially capture up to 3 $GtCO_2$ from natural gas use in industry and 1.7 Gt from natural gas-based power generation as well as a smaller amount from clean hydrogen production. CCUS on gas production and processing could capture 50–180 $MtCO_2$ per year by 2050. The availability of CCUS for natural gas use could also enable the switching of 20 percent of coal and oil used today in industry to gas as an interim step, and enable around 3 percent of coal and oil used in power generation to be switched to gas. This would deliver emissions reductions in the near term, while CCUS retrofits would avoid carbon lock-in and deliver deeper reductions over the longer term. As with all modeling analysis undertaken over such a long time-frame, there is significant uncertainty in the findings, and analysis is heavily dependent on technology, cost, and deployment assumptions.

2 The cost assumptions used in this study are based on a literature review of key technology costs carried out in January 2021, with costs aligned to cost data published by the International Energy Agency where possible.



**Figure ES.1 Industry is likely to account for the largest share of gas CCUS in a 1.75°C scenario**




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCUS = carbon capture, utilization, and storage; CO2 = carbon dioxide.

**If CCUS is not available or not deployed to address $CO_2$ emissions from natural gas, the cost of meeting Paris Agreement targets is estimated to increase.** Without the deployment of CCUS, countries that continue to produce and use natural gas will find meeting climate mitigation targets more challenging and expensive. This analysis estimates that failure to deploy CCUS with natural gas could increase the cost of meeting a 1.75°C temperature target by as much as one-third, or \$400 billion annually, by 2050. Relative to current NDC commitments, achieving a 1.75°C temperature target would cost around \$1.1 trillion in 2050 with CCUS application to natural gas use, and around \$1.5 trillion without. These higher costs arise from a combination of costlier coal CCUS, hydrogen, and renewables overbuild in power; oil-based CCUS in chemicals; electric heating technologies and coal CCS in manufacturing; and in the hydrogen sector the use of coal-based hydrogen with CCUS, or production of renewable hydrogen in regions where this is a costlier option. Even a 10-year delay in deploying CCUS on natural gas production and use (ie, to 2035) could increase the cost of achieving the 1.75°C temperature target by around \$60 billion per year by 2050.

**The need for gas CCUS is a consistent finding across multiple scenarios despite strong prospects for alternative technologies, including increased climate ambition as well as increased natural gas price assumptions.** With increasing climate ambition, the need for CCUS on natural gas production and use may become more important. In the 1.5°C scenario modeled for this study, CCUS on gas could contribute around 30 percent of total energy supply and avoid almost 7 $GtCO_2$ emissions per year in 2050. In further senstitivity analysis, depending on movements in gas prices, the role for gas CCUS could be higher than envisaged but is unlikely to be substantially lower. In a high gas price

scenario developed for this study, a 30 percent increase in gas prices reduces demand for natural gas with CCUS by less than 5 percent by 2050, due to limited cost-effective substitutes for this technology. Conversely, in a low gas price scenario, a 30 percent reduction in gas prices increases demand for natural gas used with CCUS in 2050 by 10 percent, as the combination becomes more cost-competitive than other low-carbon technologies.

**Innovations in renewable hydrogen could reduce the use of natural gas and the requirement for CCUS but will not displace it entirely, at least not immediately.** While renewable hydrogen could eventually substitute for some uses of natural gas with CCUS, the deployment of CCUS on gas has two key contributions: first, it can reduce $CO_2$ emissions not only from fuel combustion but also from industrial processes. Second, low-carbon hydrogen using natural gas and CCUS is likely to complement renewable hydrogen, which may be constrained in the near-to-medium term as it scales up from a low base, reduces in cost, and faces constraints on the availability of renewable resources as electricity demand increases.

**The continued use of gas, and in turn the need for CCUS on gas production and use, is heavily dependent on the accessibility and affordability of natural gas.** This study identifies three broad groups of countries that are likely to differ in the role of gas CCUS: large gas users, gas exporters, and constrained gas users.

- Natural gas with CCUS is particularly relevant for **large gas users** such as Mexico and the Arab Republic of Egypt with a plentiful supply of low- to moderate-cost gas, due either to domestic production or pipeline imports.
- The development of low-carbon hydrogen, using CCUS on natural gas-based CL production, could be important for **gas exporters** such as Indonesia, Qatar, and Kazakhstan with a domestic gas supply substantially in excess of demand, and large gas exports.
- CCUS and natural gas could play a more limited role for **constrained gas users** such as Vietnam and India with a limited supply of domestic and imported gas, due to small domestic reserves, limited pipeline capacity, and a reliance on more expensive LNG to meet domestic demand.

**Although accessibility and affordability of gas are important drivers, the size of the national economy and availability of alternative low-carbon power technologies may also affect the use of CCUS on natural gas.** The role of gas CCUS will differ by region across the industry and power sectors. In industry, the relative requirement for CCUS on natural gas will tend to be determined by the accessibility and affordability of natural gas. However, some constrained gas users are large economies that may use a significant amount of CCUS on natural gas at an absolute level, even when the share of industrial natural gas use is relatively low. In particular, although China is classified as a constrained gas user in this study, with gas playing a smaller role in its energy mix than in large gas users or gas exporters, in absolute terms China could constitute the largest gas CCUS opportunity, due to the large size of its economy and its energy system. In power, natural gas-generation with CCUS will tend to feature in regions with limited availability of firm and dispatchable low-carbon power, such as hydropower and nuclear. For example, many African countries, though constrained gas users, could have a strong role for gas power with CCUS due to limited opportunities for hydropower and nuclear in the power mix.

**Understanding of CCUS potential and general CCUS readiness is variable, and particularly low in developing and emerging economies.** Most of these have not conducted a detailed assessment of domestic $CO_2$ storage sites, developed a comprehensive legal and regulatory framework for CCUS, or implemented an effective policy framework to deliver CCUS projects. As a result, current and planned deployment of CCUS is still low in these countries, and remains mostly concentrated in North America, Europe, Australia and the Middle East.

**If countries continue to produce and use natural gas, policymakers will need to accelerate the assessment and deployment of CCUS, if they are to achieve national and global net zero emissions goals.** Action is needed across three key phases of CCUS deployment: planning, scale-up, and rollout:

- In the **planning phase,** policymakers who envisage a role of natural gas must then also develop a strategy for CCUS development and deployment, and ensure adequate readiness for accelerated deployment through storage characterization, developing the legal and regulatory framework, allocating public funding, planning strategic CCUS clusters, and delivering early-stage transport and storage infrastructure.

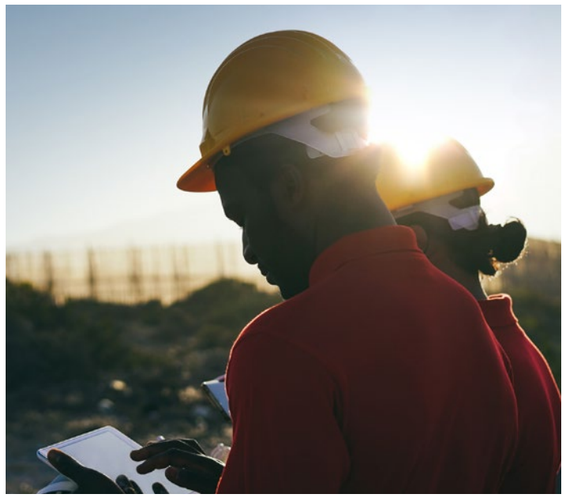


- In the **scale-up phase,** policymakers should develop and implement CCUS funding mechanisms at a national, regional, and/or global level, and provide financial support to the first CCUS projects in strategic clusters. For gas exporters looking to export low-carbon hydrogen, policymakers and business should secure bilateral agreements on hydrogen supply.
- In the **rollout phase,** policymakers should extend their support for CCUS to drive widespread deployment on all remaining natural gas production and use, while adjusting the funding/incentive mechanisms as necessary to ensure they continue to deliver value.

**CCUS on natural gas is likely to be relevant in developing and emerging economies, in particular large gas users and gas exporters. Therefore international financial institutions such as the World Bank, Asian Development Bank, and Green Climate Fund have a crucial role to play in supporting them to deliver CCUS in order to achieve the Paris Agreement goals.** International financial institutions have a role in providing technical assistance relating to CCUS; in providing grants supporting country strategies and roadmaps for CCUS uptake; in supporting the development of policies, regulations, and standards; in building capacity to design and operate CCUS projects; in supporting CCUS pilot projects in industry and across the economy; in identifying opportunities to benefit local communities, create jobs, and meet climate, environmental, and social objectives; and in mobilizing climate finance and providing access to guarantees to deliver CCUS investment that is sustainable.

**Should CCUS not be available or deployed by countries that continue to produce and use natural gas, Paris Agreement targets will become significantly more challenging and more expensive to meet – even with a high likelihood of being missed.**









# 1 Introduction

## 1.1 Background

**Achieving the full ambition of the Paris Agreement requires global greenhouse gas (GHG) emissions to reach net zero.** The Paris Agreement of 2015 aims to strengthen the global response to the threat of climate change by keeping the global temperature rise this century "well below 2°C" above preindustrial levels and to pursue efforts to limit the temperature increase even further, to 1.5°C. The Intergovernmental Panel on Climate Change (IPCC) advises that limiting the temperature increase to avoid the worst impacts of climate change will require human-caused carbon dioxide ($CO_2$) emissions to fall rapidly and ultimately reach "net zero."

**Carbon capture, utilization, and storage (CCUS) is one of the main solutions, along with clean hydrogen and biomass, to the decarbonization of hard-to-abate sectors.** In many end-use sectors, such as light transport, buildings, and light industry, electrification and the expansion of renewable electricity represent the least-cost decarbonization pathway. However, in hard-to-abate sectors such as heavy industry, electrification is not a viable mitigation pathway given the high-temperature processes and industrial process emissions. In these sectors, CCUS, clean hydrogen—either "low-carbon" hydrogen produced using natural gas with CCUS or "renewable" hydrogen produced using renewable energy, and biomass are currently considered to be the most viable solutions. CCUS can be used to capture the $CO_2$ released from the combustion of fossil fuels and from industrial processes, and the $CO_2$ released during production of low-carbon hydrogen from natural gas.

**There is a strong consensus that CCUS will be needed to achieve net zero emissions.** The vast majority of identified pathways to achieving a 1.5°C climate objective require CCUS: almost all of the 1.5°C scenarios underpinning the IPCC's 2018 Special Report on 1.5°C involve CCUS, and the International Energy Agency's (IEA's) recent Net Zero Emissions scenario involves CCUS reaching capture rates of around 5 gigatons (Gt) per year in 2050. The IEA states that limiting the availability of CCUS would increase the cost of the energy transition and require reliance on nascent and more expensive technologies. It would also increase the capital investment needed to meet climate goals in the power, industrial, and fuel transformation sectors by 40 percent. CCUS can reduce $CO_2$ emissions not only from fuel combustion but also from industrial processes in cement and other industrial sectors. The critical role of CCUS is also acknowledged by the IPCC in its special report "Global Warming of 1.5°C",[3] as well as in the International Renewable Energy Agency (IRENA) report "Reaching Zero with Renewables."[4] In IRENA's most aggressive mitigation scenario, the Deep Decarbonization Perspective scenario, CCUS is required to contribute 6 percent of annual emissions reductions in 2050, and in a recent technical paper, "Capturing Carbon,"[5] it argues that CCUS is a necessary component of the decarbonization toolbox, potentially capturing over 3 $GtCO_2$ by 2050.

CCUS is a proven technology, with 27 large-scale commercial projects in operation today. Currently, 27 operating CCUS facilities have the capacity to capture more than 35 million metric tons of carbon dioxide ($MtCO_2$) per year. This represents a rapid increase relative to average capacity of 9–13 $MtCO_2$ over the period 1990–2010. Notable existing projects include the Sleipner CCS project, which has geologically sequestered roughly 1 $MtCO_2$ per year beneath the North Sea since 1996,[6] and the Emirates Steel plant in the United Arab Emirates, the world's first commercial iron and steel CCUS facility, able to sequester 0.8 $MtCO_2$ per year. [7] Currently, the majority of $CO_2$ captured is generated at natural gas processing facilities,[8] with such projects accounting for 70 percent of CCUS activity globally. In addition to currently operational capacity, 106 new CCUS facilities with capacity to capture a further 110 $MtCO_2$ per year are in development.

3 IPCC (2018): https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf.
4 IRENA (2020): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Sep/IRENA_Reaching_zero_2020.pdf.
5 IRENA (2021): https://irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Capturing_Carbon_2021.pdf.
6 Equinor (2019): https://www.equinor.com/en/news/2019-06-12-sleipner-co2-storage-data.html.
7 CSL Forum (n.d.): https://www.cslforum.org/cslf/Projects/AlReyadah.
8 GCCSI (2020): https://www.globalccsinstitute.com/resources/global-status-report/download/.

**The importance of CCUS is being recognized through strengthened policy support and increased project development:**



In the United States, the enhanced 45Q tax credit, signed into law in 2018, has driven increased development of new CCUS facilities. The Inflation Recovery Act (IRA) (2022) includes additional incentives for CCUS.



In the Netherlands, specific provisions have been made for use of CCUS within the rules of the €5 billion Sustainable Energy Transition subsidy scheme (SDE++).



In the United Kingdom, the March 2020 budget provided over £800 million to establish CCUS clusters on at least two UK sites this decade and in October 2021 the UK Government announced it had selected two proposed schemes, the East Coast Cluster and HyNet schemes for funding assessment.



In Norway, a $CO_2$ tax has existed on all oil and gas operations on the continental shelf since 1991, at a rate of $63/t$CO_2$; in 2020, $1.2 billion of public financing was committed to the Northern Lights CCS project, currently under development in the North Sea.



In 2021, Germany announced the €100 million per year "$CO_2$ avoidance and use in raw material industries" CCUS support program.

Linked to this sustained policy focus, existing CCUS capacity, though limited, more than doubled over 2010–20, from 15 $MtCO_2$ per year in 2010 to around 35 $MtCO_2$ per year in 2020. Following a sharp reduction in the number of planned CCUS projects between 2010 and 2017, capacity in development is now also increasing rapidly, from 25 $MtCO_2$ per year under development in 2017 to 110 $MtCO_2$ per year in 2021.

**Policymakers and businesses are investing in low-carbon hydrogen.** Low-carbon hydrogen is the dominant clean hydrogen produced today. It accounts for around 40 percent of the 6.7 million tons a year of announced production capacity for clean hydrogen for 2030, and around 50 percent of "mature" announced capacity, whereby the investment is either in a planning stage, has passed a final investment decision, or is associated with a project under construction, already commissioned or operational. Example early-stage projects include Project Pouakai Hydrogen Production in New Zealand, the Hydrogen Energy Supply Chain project in Australia, and the East Coast Cluster and Hynet North West projects in the United Kingdom. Quest CCS in Alberta, Canada—the largest clean hydrogen project in operation today—has captured and stored over 5 $MtCO_2$ since beginning operations in 2015. The facility decarbonizes gas streams from three hydrogen manufacturing units, before transporting captured $CO_2$ for nearby, dedicated geological storage.

**The World Bank's Climate Change Action Plan 2021–25, which sets out how the Bank will address climate change in its pursuit of poverty eradication and shared prosperity, confirms its support for CCUS.** The Action Plan recognizes that CCUS may be an important lever for decarbonization as the Bank works with countries to prepare energy plans that incorporate low-carbon energy scenarios. In this context, this report looks at the role of gas CCUS and offers a roadmap for deep decarbonization using natural gas CCUS.

**CCUS is not applicable or available in all circumstances, and challenges with CCUS deployment remain, with the roll-out of the technology falling well behind expectations.** CCUS deployment is well behind the pathway necessary to reach the levels of deployment required in IEA, IPCC and IRENA analysis. The IEA considers CCUS deployment to be "not on track" in both



power generation and industry. Challenges associated with the roll-out of CCUS are varied. Although, globally, $CO_2$ storage capacity is considered to be adequate to meet the world's needs, at the national and local levels there is uncertainty over the $CO_2$ storage potential, with $CO_2$ storage exploration and characterization requiring investment and long lead-times. In addition, a robust legal and regulatory framework needs to be in place to ensure that CCUS operational health and safety risks are managed and to provide certainty on the long-term stewardship of the stored $CO_2$. CCUS legal and regulatory frameworks are in place in a range of jurisdictions, including in the US, Europe and Australia, but in general readiness to deploy CCUS is low, particularly in developing and emerging economies. CCUS is also a capital-intensive technology, with abatement costs ranging from $15–120/t$CO_2$ – higher in many instances than abatement costs from renewable energy or energy efficiency. Public acceptance of CCUS can also be a challenge, with perceptions of technology risks as well as widespread concerns about competition with renewable technologies or perpetuation of fossil fuels. In many instances, CCUS may not be applicable or available, or more affordable alternatives may exist.

**The report focuses on five key opportunities for gas CCUS in:**

- Gas-based industry;
- Gas power generation;
- Low-carbon hydrogen production;
- Gas and liquefied natural gas (LNG) production; and
- Unlocking fuel switching opportunities in the near-to-medium term.

### Box 1. CCUS – relevant sectors, readiness levels and impacts on water consumption

The cost of $CO_2$ capture and its readiness level is determined by the sector in which it is deployed. Combustion of fossil fuels produces $CO_2$, and capturing this $CO_2$ is known as post-combustion $CO_2$. Depending on whether the fuel is combusted in air or pure oxygen (in a process called oxy-combustion), the $CO_2$ concentration in the post-combustion stream varies. Apart from the CO2 produced as a result of combustion, certain high emission sectors produce $CO_2$ as a by-product of the production or purification process. In the case of natural gas production, $CO_2$ is separated from natural gas during gas processing, to ensure natural gas meets the pipeline standards required for its transport. In this process, $CO_2$ and other impurities are separated from natural gas, producing a highly concentrated $CO_2$ stream that can be captured and purified for storage or use. Similarly, for hydrogen, ammonia and methanol produced from fossil fuels, $CO_2$ is produced as a by-product of the production process, resulting in a high-concentration $CO_2$ stream that can be captured for purification, followed by storage. In the case of cement production, $CO_2$ captured is a combination of by-product $CO_2$ from the calcination of limestone, and post-combustion $CO_2$. The final $CO_2$ stream in cement industries is of low concentration. There are currently 27 commercial operating CCUS plants across the world, as of 2022. Several other CCUS projects have been planned or are in pilot and demonstration stages. The cost, readiness level and examples of CCUS projects are summarized in the table below. Alongside the capture of $CO_2$, the transport and storage of $CO_2$ are also important factors to take into consideration, as summarized in the second table below.

### Box 1. CCUS – relevant sectors, readiness levels and impacts on water consumption

**CCUS readiness level, costs and relevant projects**

| | $CO_2$ stream concentration[9] | Technology readiness level (TRL)[10] | Levelised cost of $CO_2$ capture ($/$CO_2$)[11] | Examples of commercial and operating projects[12] |
|---|---|---|---|---|
| Gas processing | High | TRL 9–11 | $15–25 | Century Plant (USA), CNOOC South China Offshore CCS (China) |
| Cement production | Low | TRL 4–7 | $60–120 | Low Emissions Intensity Lime and Cement (Belgium) |
| Iron and steel production | Low | TRL 4–9 | $40–100 | Abu Dhabi CCS (UAE) |
| Power generation | Low | TRL 3–9 | $50–100 | Boundary Dam 3 CCS Facility (Canada) |
| $H_2$ production (steam methane reforming) | High | TRL 9–11 | $50–80 | Air Products Steam Methane Reformed (USA), Quest CCS (Canada) |
| Ammonia and methanol production | High | TRL 9–11 | $25–35 | Arkalon $CO_2$ compression facility (USA), Bonanza BioEnergy CCUS EOR (USA), Illinois industrial CCS (USA) |

**$CO_2$ transport and storage readiness levels**

| | Technology readiness level (TRL)[13] | Status of development[14] |
|---|---|---|
| $CO_2$ transport – pipeline | TRL 10 | Over 8,500 km of $CO_2$ pipelines exist across the world |
| $CO_2$ transport – ship | TRL 5–7 | Large-scale transportation of $CO_2$ by ship has not yet been demonstrated but is being developed as part of the Norwegian Longship CCUS hub project |
| $CO_2$ storage – EOR | TRL 11 | $CO_2$ EOR has been undertaken commercially in North America since the 1960s |
| $CO_2$ storage – saline formations | TRL 9 | $CO_2$ has been stored at commercial scales in saline aquifers since 1996 with the commencement of the Norwegian Sleipner CCS project |
| $CO_2$ storage – depleted oil and gas fields | TRL 7 | Some pilot and demonstration projects exist, but no large-scale development to date |

9 IEA, 2019, Is carbon capture too expensive?, Retrieved from: https://www.iea.org/commentaries/is-carbon-capture-too-expensive.
10 IEA, 2020, Energy Technology Perspectives — Clean Energy Technology Guide.
11 IEA, 2019, Is carbon capture too expensive?, Retrieved from: https://www.iea.org/commentaries/is-carbon-capture-too-expensive.
12 Global CCS Institute, 2022, $CO_2$re facilities database, Retrieved from: https://co2re.co/ccsreadiness.
13 IEA, 2020, Energy Technology Perspectives — Clean Energy Technology Guide.
14 IEA, 2020, CCUS Technology Innovation, Retrieved from: https://www.iea.org/reports/ccus-in-clean-energy-transitions/ccus-technology-innovation.



## 1.2 Approach

**To assess the potential need for CCUS on natural gas production and use and develop a roadmap for CCUS in the natural gas sector, the report used a two-part approach.**

1. **Energy system modeling.** To assess the potential need for gas CCUS in achieving the Paris Agreement climate mitigation targets and net zero emissions, at the global level and across key world regions, this study combines energy system modeling with electricity system modeling that covers the range of national circumstances relevant to the deployment of gas CCUS.
2. **Case studies.** To refine the assessment of the global opportunity for gas CCUS, and to generate insights on readiness for gas CCUS, the report presents several detailed case studies on the role of CCUS and its prospects for gas CCUS in a number of developing and emerging economies.

**The report then develops a roadmap for the deployment of CCUS in the natural gas sector.** The report identifies barriers to deployment of gas CCUS; assesses the progress of national economies—with a focus on developing and emerging economies—in addressing these barriers and achieving readiness for deployment of gas CCUS; and identifies the actions for policymakers, supported by international financial institutions, to accelerate this deployment.

## 1.3 Structure of this report

This report sets out the findings of this research in the following five chapters:

- **Chapter 2: A global and regional assessment** identifies the contribution of gas CCUS to achieving the Paris Agreement and global net zero emissions targets, overall and for four main gas CCUS opportunities. First, it characterizes the overall role of gas CCUS at the global level. It then characterizes in detail four main gas CCUS applications: the use of CCUS on gas in industry, in power generation, in low-carbon hydrogen production, and in natural gas production. It also characterizes the opportunities that gas CCUS could unlock for fuel switching in the industry and power sectors. Finally, it assesses the readiness for gas CCUS globally.
- **Chapter 3: National role of gas CCUS** assesses the potential deployment of gas CCUS in 11 developing and emerging economies. Based on a global and regional assessment and national trends in energy use, it characterizes the potential gas CCUS requirement across four applications. It considers how costs and benefits of gas CCUS could vary depending on the location of $CO_2$ emissions sources, $CO_2$ storage, and the potential to leverage opportunities for enhanced oil recovery. It assesses the readiness for gas CCUS in each country studied. Finally, it identifies actions for international financial institutions to support policymakers in developing and emerging economies to accelerate deployment of gas CCUS.
- **Chapter 4: Regional cooperation on gas CCUS** assesses the benefits of cross-border cooperation on $CO_2$ storage. Based on four regional case studies, it examines prospects for $CO_2$ export and import between countries and estimates the additional gas CCUS opportunity that can be unlocked through cross-border cooperation.
- **Chapter 5: A roadmap to deploy CCUS on natural gas** identifies actions for policymakers, supported by international financial institutions, to accelerate deployment of CCUS where natural gas continues to be produced and used to support achievement of the Paris Agreement and net zero emissions goals. It identifies the policy actions needed at three stages of CCUS deployment: planning, scale-up, and rollout. It then offers recommendations for three key groups of countries: large gas users, gas exporters, and constrained gas users.
- **Chapter 6: Country case studies** provides additional detail on the current status of CCUS and the prospects for gas CCUS across the four applications in each of the 11 developing and emerging economies considered as part of this study: Brazil, China, Egypt, India, Indonesia, Kazakhstan, Mexico, Mozambique, Saudi Arabia, Ukraine, and Vietnam.





# 2 Global and regional requirement for CCUS on gas

## 2.1 Introduction

**This chapter identifies the contribution of CCUS on natural gas production and use to achieving the Paris Agreement and global net zero emissions goals, overall and for four main gas CCUS applications.** First, it estimates the overall deployment of gas CCUS at the global level. It then characterizes in detail four main gas CCUS applications: the use of CCUS on gas use in industry, power generation, low-carbon hydrogen production, and natural gas production. It also characterizes the opportunities that gas CCUS could unlock for fuel switching in the industry and power sectors. Finally, it assesses the readiness for gas CCUS globally.

**For these four applications, this study considers how the scale and deployment of gas CCUS may vary across three broad groups of countries: large gas users, gas exporters, and constrained gas users.** The accessibility and affordability of natural gas drive gas use today are likely to be strong drivers of gas CCUS in the future. Countries are defined with respect to the accessibility and affordability of gas, as follows:

1. **Large gas users are countries with a plentiful supply of low- to moderate-cost gas.** They may produce the majority of their gas domestically or have good access to gas via pipeline imports. They are defined as countries with a share of natural gas in the energy mix of more than 20 percent, that receive less than one-third of their gas imports as LNG, and that export less than 20 percent of their domestic natural gas production. Large gas users include the United States, Germany, Mexico, and the Arab Republic of Egypt. CCUS could play a particularly important role for large users. Many large gas users have a developed domestic oil and gas industry and are therefore likely to have the technical capacity to store $CO_2$ in domestic stores.
2. **Gas exporters are countries with a domestic gas supply substantially in excess of demand, and large gas exports.** They are defined as countries that export more than 20 percent of their domestic natural gas production. Gas exporters include Australia, Qatar, Indonesia, and Kazakhstan. As with large gas users, gas CCUS is likely to be a cost-effective decarbonization technology for gas exporters. Further, the scale of domestic resources and presence of a mature gas export industry could support export of low-carbon hydrogen to countries with more limited energy resources. All gas exporters have a developed domestic oil and gas industry and are therefore likely to have the technical capacity to store $CO_2$ in domestic stores.
3. **Constrained gas users are countries with a limited supply of domestic and imported gas.** They have small domestic gas reserves and limited pipeline capacity and would require import of more expensive LNG to meet a large share of energy demand with natural gas. Constrained gas users are defined as countries with a share of natural gas in the energy mix of less than 20 percent or which receive more than one-third of their gas imports as LNG; and which export less than 20 percent of their domestic natural gas production. Constrained gas users include China, Japan, India, and Vietnam. CCUS may play a more limited role for constrained users, focusing on applications with the highest value in minimizing the cost of reducing emissions, and export of low-carbon hydrogen is not envisaged. Some constrained users have a developed domestic oil and gas industry and may need to export captured $CO_2$ to neighbors more likely to have $CO_2$ storage capabilities.

**The scale of gas CCUS will also depend on the size of the national energy system.** While the role of gas CCUS relative to alternative decarbonization solutions will be partly determined by the availability and affordability of natural gas, the overall volume of gas CCUS will also be determined by the size of the national economy. In particular, although China is classified as a constrained gas user in this study, with gas playing a smaller role in its energy mix than in large gas users or gas exporters, in absolute terms China sees the largest deployment of gas CCUS, due to the large size of its economy and its energy system.

Table 1 characterizes the regions modelled in this study based on the definitions above.

Table 1. Characterization of regions modelled in this study

| Region | Example countries | % gas in energy mix | % gas exported | % LNG in gas demand | Profile |
|---|---|---|---|---|---|
| **Africa (AFR)** | South Africa | 3 | 0 | 0 | Constrained user |
| | Mozambique | 7 | 83 | 0 | Gas exporter |
| **Australia (AUS)** | Australia | 25 | 68 | 0 | Gas exporter |
| **Canada (CAN)** | Canada | 36 | 31 | 1 | Gas exporter |
| **China (CHI)** | China | 8 | 0 | 27 | Constrained user |
| **Central and South America (CSA)** | Brazil | 11 | 0 | 8 | Constrained user |
| | Argentina | 54 | 0 | 7 | Large gas user |
| **Eastern Europe (EEU)** | Poland | 15 | 0 | 33 | Constrained user |
| **Former Soviet Union (FSU)** | Kazakhstan | 25 | 44 | 0 | Gas exporter |
| | Ukraine | 27 | 0 | 0 | Large gas user |
| **India (IND)** | India | 6 | 0 | 50 | Constrained user |
| **Japan (JPN)** | Japan | 23 | 0 | 100 | Constrained user |
| **Middle East (MEA)** | Saudi Arabia | 37 | 0 | 0 | Large gas user |
| | Egypt, Arab Rep. | 54 | 0 | 5 | Large gas user |
| | Qatar | 89 | 74 | 0 | Gas exporter |
| **Mexico (MEX)** | Mexico | 36 | 0 | 9 | Large gas user |
| **Other Developing Asia (ODA)** | Indonesia | 17 | 38 | 0 | Gas exporter |
| | Vietnam | 10 | 0 | 0 | Constrained user |
| **Korea, Rep. (SKO)** | Korea, Rep. | 17 | 0 | 100 | Constrained user |
| **United States (USA)** | United States | 32 | 3 | 0 | Large gas user |
| **Western Europe (WEU)** | Germany | 24 | 0 | 0 | Large gas user |
| | France | 15 | 0 | 30 | Constrained user |

Sources:IEA World Energy Balances, BP Statistical Review of World Energy, and Rystad Energy.
Note: The regions listed here are represented in the TIAM-Grantham Energy System Model used in this study and differ from the World Bank's classification of world regions. The country analysis of Ukraine was undertaken before the Russian invasion and therefore may change significantly from what is presented here. LNG = liquefied natural gas.



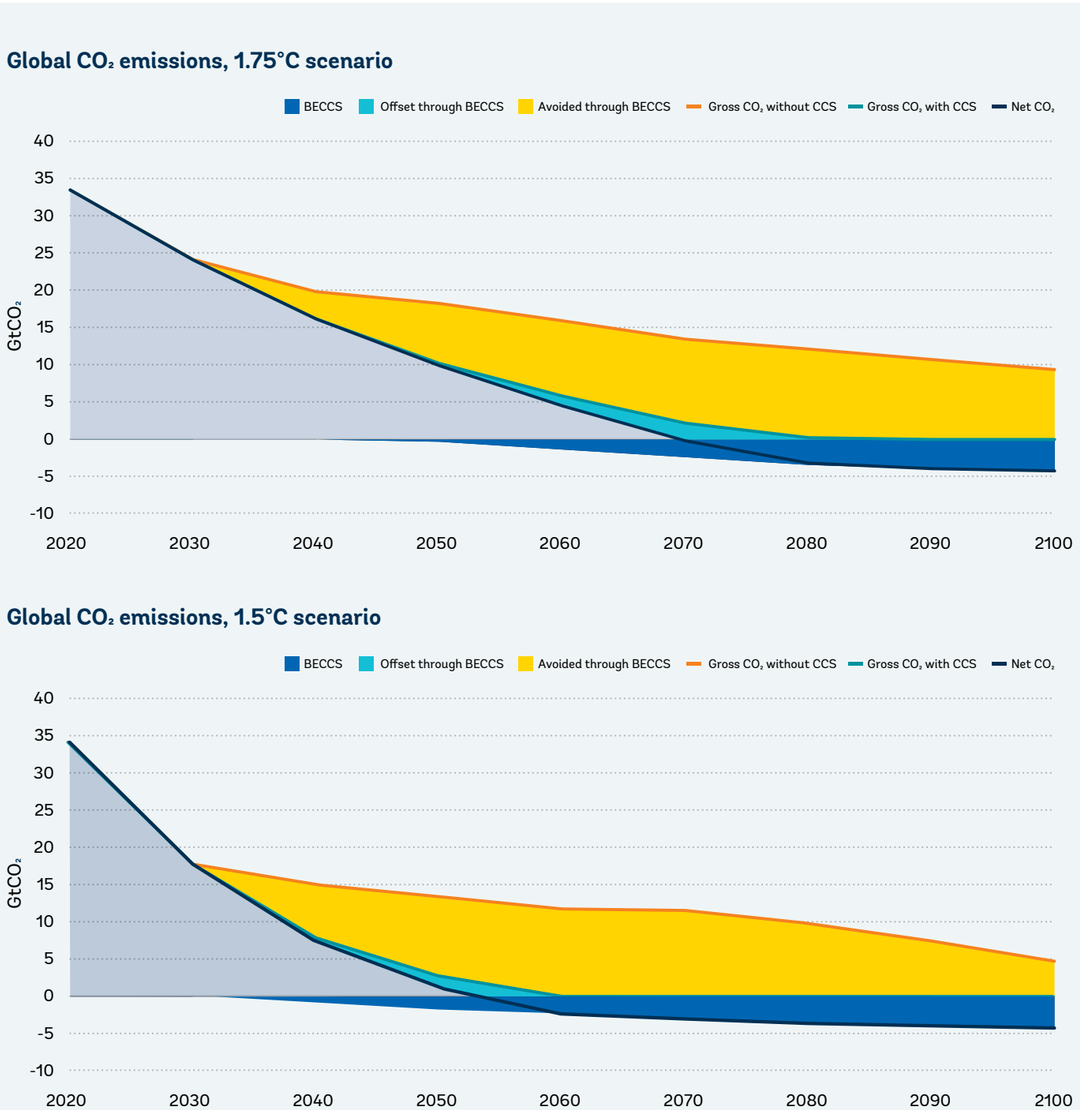
## 2.2 The deployment of CCUS on natural gas to meet Paris Agreement goals and global net zero emissions

### Box 2. The contribution of gas CCUS to climate goals: Key messages

- **If countries continue to produce and use natural gas, CCS may be the only technology available to mitigate some emissions, particularly in hard-to-abate industrial sectors, or could be used to reduce the overall cost of meeting Paris Agreement targets.** Specifically:
- **CCS may be the most economically viable, and in some cases the only, mitigation option available to address emissions from natural gas use in some hard-to-abate industries.**
  - **In countries with low-cost natural gas available, deploying CCS on gas power generation may reduce the costs of fully decarbonizing the electricity grid.**
  - **While the specific contribution of low-carbon hydrogen to total CL supply is highly uncertain, it is likely to play a valuable role in developing a CL market and is likely to remain competitive in regions with abundant cheap natural gas.**
  - **If natural gas continues to be used by countries, emissions associated with gas production and supply must be addressed, including through CCS on natural gas and LNG production.**
- **Scenario analysis undertaken as part of this study found that the application of CCS on natural gas production and use could play a signficant role in achieving the objectives of the Paris Agreement.** Gas CCUS could contribute almost 20 percent of total energy supply and avoid 5 $GtCO_2$ emissions in 2050 in a 1.75°C scenario. This ensures that any long-term use of natural gas as a fuel source is consistent with the pathway to net zero. Long-term opportunities for gas CCUS in power generation and industry could also unlock opportunities for switching from coal and oil to natural gas in the near-to-medium term. Around 3 percent of coal and oil used today in power generation, and almost 20 percent used in industry, could switch to gas with CCUS over the period to 2050.
- **With increasing climate ambition, gas CCUS would play a still greater role in reducing $CO_2$ emissions**. In the 1.5°C scenario modeled for this study, gas could contribute over 25 percent of total energy supply and avoid around 8 $GtCO_2$ emissions in 2050.
- **Failure to deploy gas CCUS could increase the cost of achieving 1.75°C by around one-third, or $400 billion per year by 2050, relative to achieving these targets with the inclusion of gas CCUS.**[15] These costs are driven by the need to shift to costlier climate solutions across the power and industry sectors.
- **Innovations in renewable hydrogen could reduce the role of gas CCUS but will not displace it entirely.** While renewable hydrogen could eventually substitute for some gas CCUS, gas CCUS has two key advantages: first, it can reduce $CO_2$ emissions not only from fuel combustion but also from industrial processes. Second, gas CCUS is likely to complement renewable hydrogen, which may be constrained in the near-to-medium term as it scales up from a low base and faces constraints on the availability of renewable resources as electricity demand increases.

15 The cost increase is over and above the cost of achieving current Nationally Determined Contribution (NDC) commitments, which form the baseline of both scenarios.

**Figure 1. Net zero emissions can be achieved through reducing fossil fuel use, capturing $CO_2$ emissions with CCUS, and removing $CO_2$ with bioenergy with carbon capture and storage**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: BECCS = bioenergy with carbon capture and storage; $CO_2$ = carbon dioxide; CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

This section considers the contribution of gas CCUS to achieving the Paris Agreement goals and global net zero emissions. First, it summarizes the potential application of decarbonized natural gas in meeting a 1.75°C climate objective, drawing on a cost-optimized energy scenario developed for this study. It summarizes the role of CCUS on natural gas in four specific applications: in power generation, industry, low-carbon hydrogen production, and natural gas production. Based on applications in power generation and industry, the report identifies the potential offered by gas CCUS for switching from coal or oil to natural gas. The report considers two key uncertainties around the role of gas CCUS: gas prices and alternative decarbonization solutions. The report estimates the value of gas CCUS in achieving the Paris Agreement goals and a global net zero emissions objective, contrasting the cost of decarbonization in a central 1.75°C scenario with its cost in a scenario with delayed gas CCUS, and in a scenario without CCUS deployed on natural gas. Finally, the report considers the implications of a 1.5°C temperature target on gas CCUS deployment patterns.

To accurately assess the potential contribution of gas CCUS, the report develops plausible and realistic energy scenarios, integrating a whole energy system model with a detailed electricity system model. The whole energy system modeling was carried out in partnership with Imperial College London using the Grantham Institute's Times Integrated Assessment Model (TIAM-Grantham). This is a multiregion, least-cost optimizing model of the world energy system, generating decarbonization pathways in the power generation, transport, buildings, and industry sectors. The full energy sector analysis is complemented with detailed electricity system modeling using Imperial College's Whole-energy System Investment Model (WeSIM). WeSIM includes a detailed characterization of electricity system resources and models' reliability needs in detail, including adequacy, inertia, reserve, and response.[16] Finally, the two modeling approaches are integrated to develop detailed climate scenarios, which assess the role and value of gas CCUS across sectors.

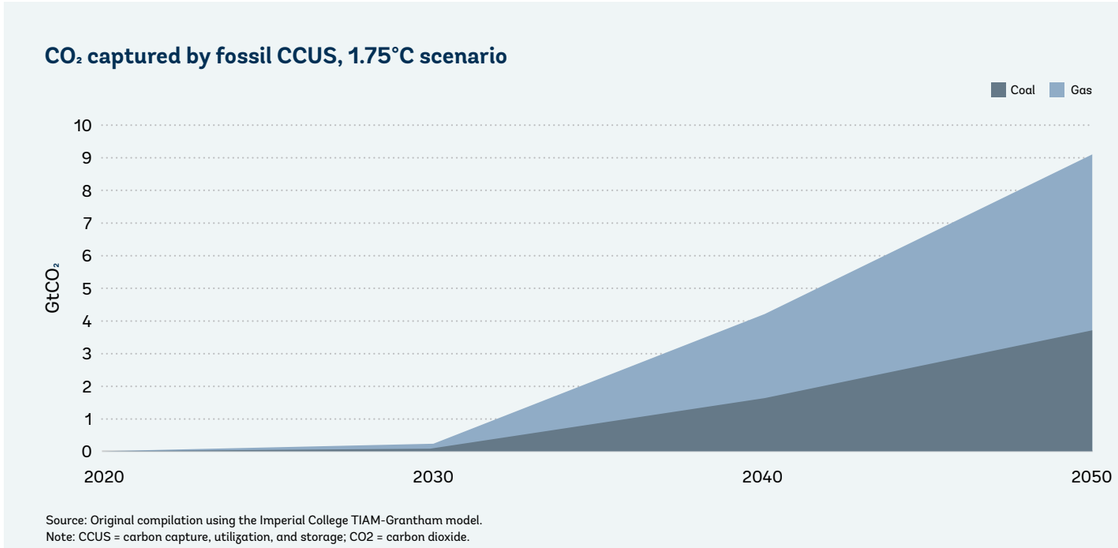
Scenarios are modeled for two temperature outcomes: a "well below 2°C" central scenario that achieves a 1.75°C temperature outcome in 2100, and a high ambition scenario that achieves a 1.5°C temperature outcome. These scenarios are consistent with the Paris Agreement target of limiting the increase in global temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels.

In a 1.75°C scenario, net zero emissions are achieved by around 2070, through a combination of reducing fossil fuel use through renewables and energy efficiency, CCUS, and negative emissions technologies. Figure 1 shows global $CO_2$ emissions over the period to 2100 in a 1.75°C scenario. Gross emissions decrease by around 60 percent by 2070 due to a shift from the use of fossil fuels to alternative technologies. The capture of $CO_2$ from fossil fuels by CCUS reduces net emissions by around 8 $GtCO_2$ in 2050 and 11 Gt in 2070. The remaining emissions reductions are provided by bioenergy with carbon capture and storage (BECCS). In the 1.75°C scenario developed for this study, BECCS reduces net emissions by around 2.5 $GtCO_2$ as of 2070. As a result, gross $CO_2$ emissions are almost entirely offset by 2070, while the global energy system reaches net zero emissions.

Analysis suggests a significant contribution of CCUS on natural gas in achieving a 1.75°C outcome, representing 60 percent of fossil fuel CCUS, and almost 20 percent of primary energy demand by 2050. Figure 2 shows $CO_2$ captured by fossil fuel CCUS over the period to 2050 in a 1.75°C scenario. Growth in gas CCUS is slow initially as low-cost climate solutions such as renewables are adequate to deliver much of the necessary emissions reductions. However, gas CCUS grows substantially beyond 2030 as deeper emissions reductions are needed, and accounts for around 60 percent of fossil fuel CCUS by 2050, equivalent to a 5 $GtCO_2$ reduction of gross emissions. Figure 3 shows global primary energy demand over the period to 2050 in a 1.75°C scenario. Primary energy demand remains broadly constant to 2050 as the efficiency gains from electrification and energy efficiency offset growth in demand, while use of unabated coal, oil, and gas falls by over 60 percent. Gas with CCUS accounts for almost 20 percent of primary energy demand and over 50 percent of total gas demand by 2050.

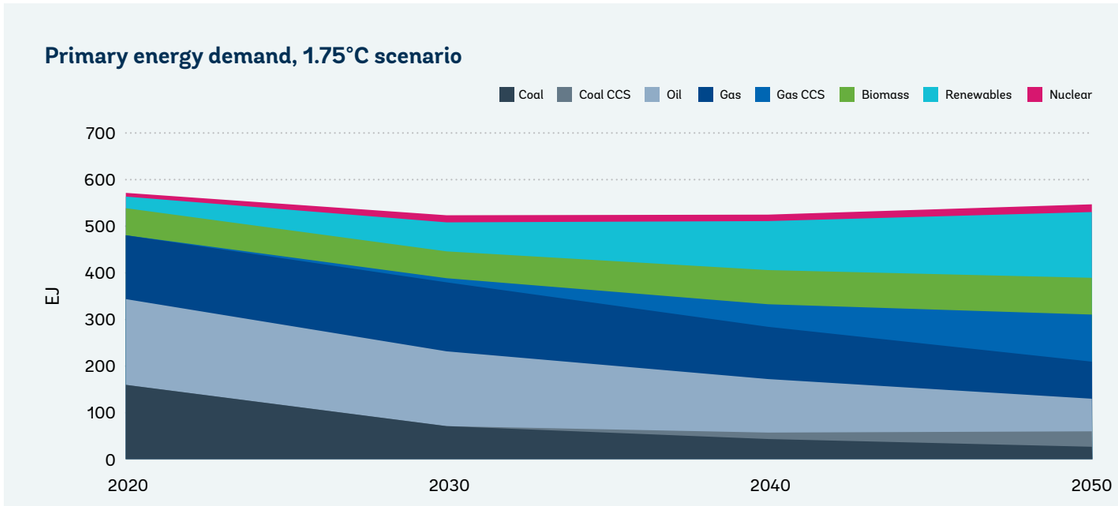
16 Specifically, WeSIM models scenarios that account for adequacy (ensuring that supply and demand are balanced at all times of the year), inertia (ensuring that there are sufficient turbine-based plants in the system to reduce sudden deviations in the frequency of the electricity system), and frequency response (ensuring that there is sufficient spare generation capacity to increase frequency in the event of a deviation).

**Figure 2. Gas CCUS accounts for around 60% of all fossil fuel CCUS by 2050**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: CCUS = carbon capture, utilization, and storage; CO2 = carbon dioxide.

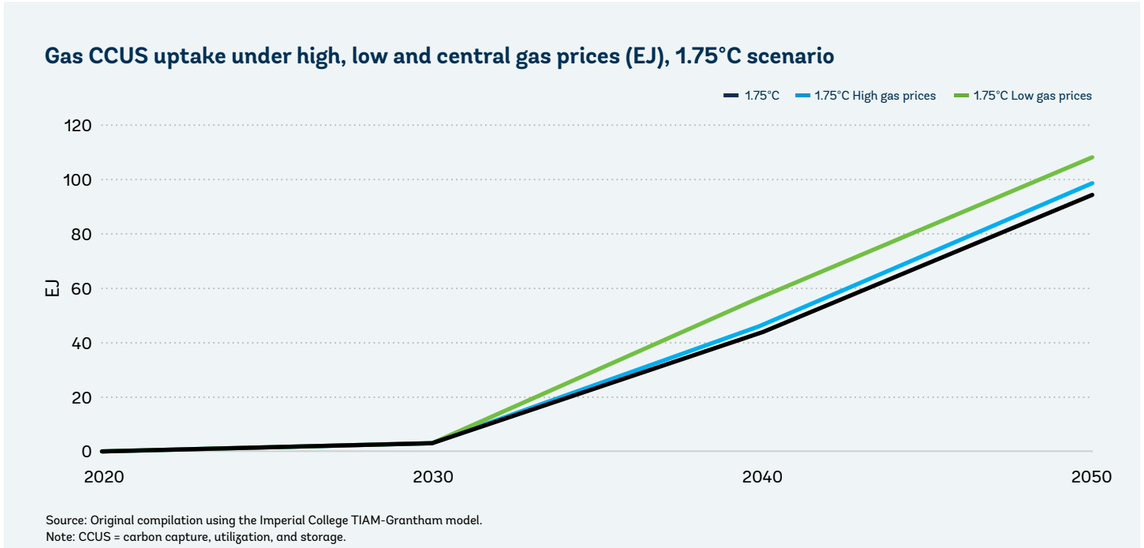
**Figure 3. Gas CCUS could account for almost 20% of primary energy demand and over 50% of natural gas use by 2050**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.



**Figure 4. Gas CCUS deployment increases as gas prices fall, while retaining a substantial role under high prices**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: CCUS = carbon capture, utilization, and storage.

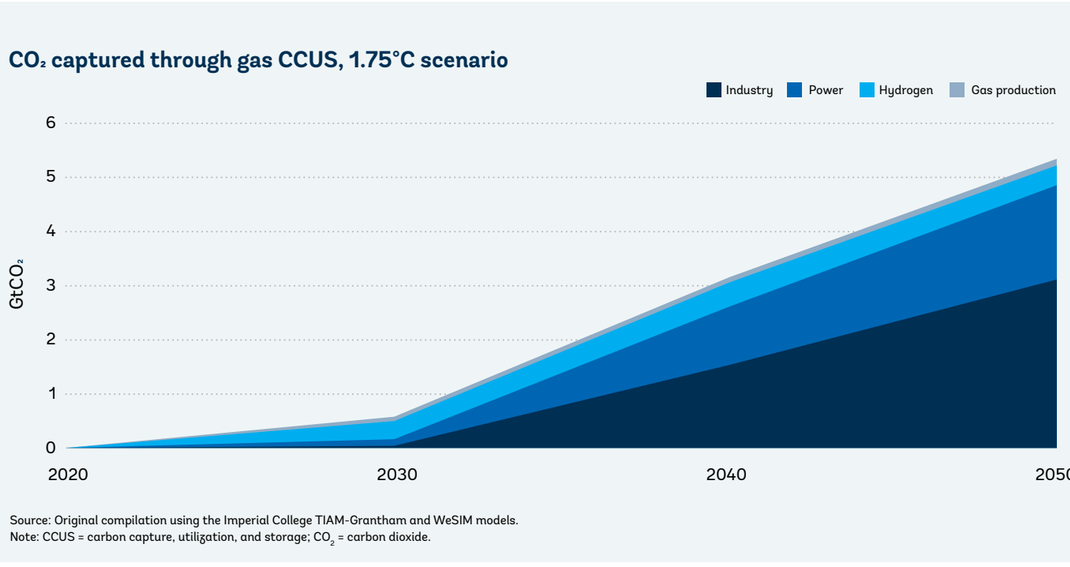
**Depending on movements in gas prices, the role for gas CCUS could be larger than envisaged but is unlikely to be substantially smaller.** Figure 4 shows gas CCUS uptake under high, low, and central gas prices in a 1.75°C scenario, over the period to 2050. Modelled sensitivities differ from the baseline assumptions as below:

1. In the *low* gas price scenario, prices are approximately 30 percent lower than baseline.
2. In the *high* gas price scenario, prices are approximately 30 percent higher than baseline.

In the low gas price scenario, demand for gas CCUS is 10 percent higher than under baseline assumptions by 2050, indicating gas CCUS becomes a more competitive decarbonization option as gas prices fall. In the high gas price scenario, demand for gas CCUS falls by less than 5 percent by 2050, likely due to limited low-carbon alternatives in industry, and limited demand for hydrogen over the same period. Low-carbon hydrogen production, and thus deployment of gas CCUS, becomes more sensitive to gas prices beyond 2050 in the scenarios created for this study, due to demand for hydrogen increasing substantially in the latter half of the century.

**The primary application of gas CCUS is assessed to be in decarbonizing heavy industry followed by power generation, with supplementary applications in low-carbon hydrogen production and natural gas production.** Figure 5 shows gas CCUS uptake by application in a 1.75°C scenario over the period to 2050. Total $CO_2$ captured by gas CCUS reaches around 5 Gt by 2050. Around 55 percent of $CO_2$ captured is from industry, due to a lack of alternative cost-effective decarbonization options. Power generation accounts for around 35 percent of $CO_2$ captured, and low-carbon hydrogen production accounts for around 5 percent. Although overall gas CCUS in industry plays a larger role than in power, in the early stages, gas CCUS in power is deployed more rapidly due to the rapid pace of power sector decarbonization required. Further, CCUS with natural gas production could reduce $CO_2$ emissions by 180 $MtCO_2$ per year in 2050, or 2 percent of the total 5 $GtCO_2$ emissions reduced by gas CCUS overall.

**Figure 5. Industry is likely to account for the largest share of gas CCUS in a 1.75°C scenario**




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide.

**Fuel switching from coal and oil to natural gas can offer substantial near-term emissions reductions, provided that methane emissions from upstream and downstream natural gas are reduced.** Combustion of natural gas releases 42 percent less $CO_2$ than combustion of coal, and 24 percent less than combustion of oil. Shifting from coal and oil to natural gas in the industry and power sectors is a widely recognized option to reduce $CO_2$ emissions in the near term. However, around 41 Mt of methane was emitted from upstream and downstream natural gas operations in 2020, raising the contribution to global warming of natural gas production and use. Reducing methane emissions from upstream and downstream natural gas is therefore necessary to maximize the GHG reductions achieved by switching from coal and oil to natural gas. In the IEA's Paris-aligned Sustainable Development Scenario, methane emissions fall 75 percent to 10 Mt by 2040, and the role of gas CCUS assessed in this study is contingent on comparable reductions.

**Long-term opportunities for gas CCUS in power generation and industry could facilitate a 20 percent reduction in coal and oil use in industry and a 3 percent reduction in coal and oil use in power through switching to natural gas – conversely, switching to natural gas without addressing supply chain emissions and the deployment of CCUS risks locking in future natural gas emissions.** Deployment of gas CCUS in the long term creates opportunities for fuel switching to reduce coal and oil use in the near-to-medium term, provided gas combustion units are made CCUS-ready when the fuel switching occurs and CCUS is subsequently retrofitted, and upstream emissions are minimized. Around 20 percent of coal and oil used in industry today could be switched to gas, with the future application of CCUS; while only around 3 percent of coal and oil used in power today could be switched to gas, as renewables will replace the majority of these fuels in the power sector.

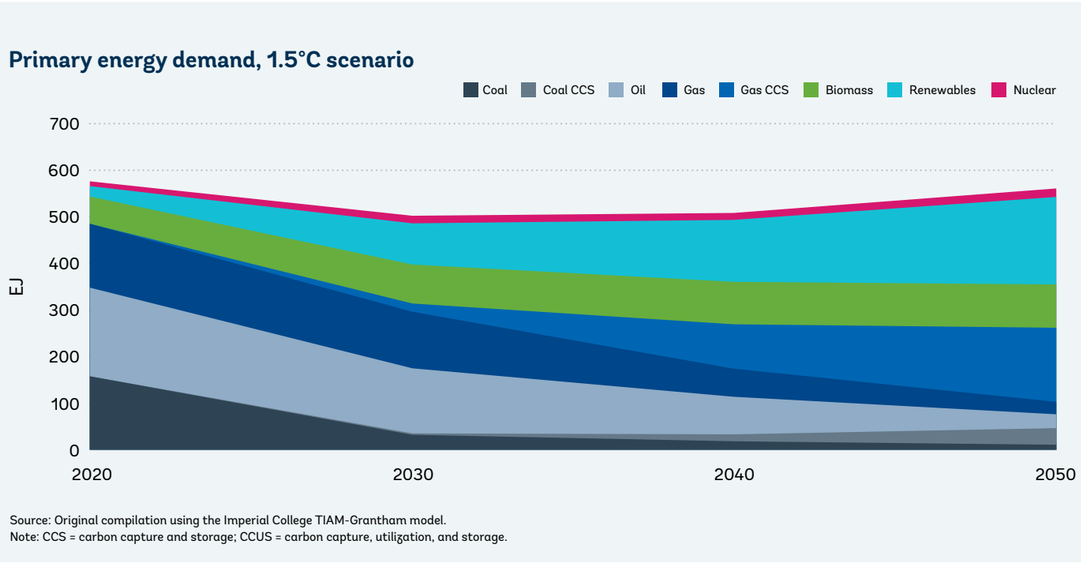
**Failure to deploy gas CCUS would lead to a substantial increase in costs to stay on a 1.75°C path.** To reach the 1.75°C target without the deployment of CCUS on natural gas would require a shift to more expensive low-carbon technologies. Failure to deploy CCUS would increase the cost of meeting a 1.75°C temperature target by around one-third, or $400 billion per year. Relative to current NDC commitments, achieving a 1.75°C temperature target would cost around $1.1 trillion in 2050 with gas CCUS, and around $1.5 trillion without. These higher costs arise from:

- In the power sector, a combination of costlier coal CCUS,[17] hydrogen, the need to "overbuild" renewables and additional battery storage to ensure adequate generation at times of low renewables output.
- In the industry sector, the use of costlier oil-based CCUS in the chemicals sector, and electric heating technologies and coal CCUS to provide high-temperature heat across manufacturing industries.
- In hydrogen production, the use of coal-based hydrogen with CCUS instead of gas-based hydrogen with CCUS, or production of renewable hydrogen in regions where this technology is less competitive.

Even a 10-year delay in the deployment of CCUS on natural gas to 2035 could increase the cost of achieving the 1.75°C temperature target by around $60 billion per year in 2050. In addition, failure to deploy gas CCUS could result in an inability to meet the temperature target, if alternative technologies cannot be deployed in its place.



**Figure 6. In a 1.5°C scenario, the role of gas with CCUS in primary energy demand grows significantly**

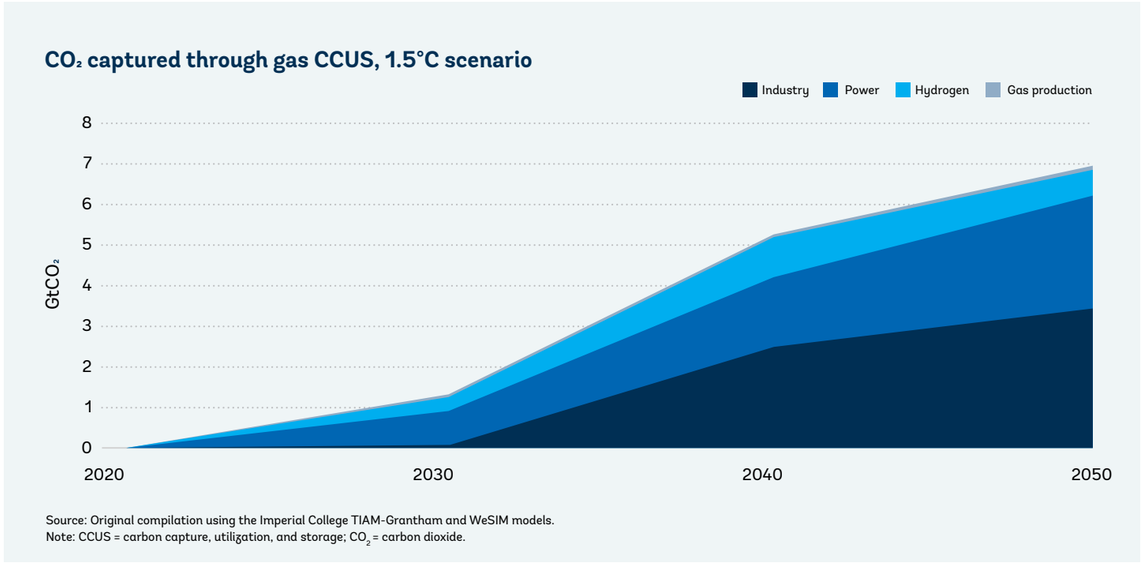



Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

**Deployment of CCUS on natural gas is estimated to be even more necessary in achieving a 1.5°C outcome, accounting for over one-quarter of primary energy demand by 2050.** Figure 6 shows global primary energy demand in a 1.5°C scenario over the period to 2050. Primary energy demand remains broadly constant; use of oil and unabated coal and gas falls by around 85 percent, with residual use occurring in the industry and transport sectors. Gas with CCUS represents almost 30 percent of global primary energy demand by 2050, compared to around 20 percent under a 1.75°C scenario, and the second-largest energy source after renewables. Under a 1.5°C scenario, the majority of gas is decarbonized, with gas CCUS representing around 85 percent of total natural gas demand by 2050.

17 Gas CCUS is substantially cheaper than coal CCUS for new plant. The IEA Greenhouse Gas R&D Programme (IEAGHG) estimates the cost of coal CCUS at $2,400–2,650 per kilowatt (kW), gas CCUS at $1,500–1,600 per kW; similarly, IEAGHG estimates the efficiency of a coal CCUS plant at 33–36 percent, and a gas CCUS plant at 44–45 percent .

Figure 7. Gas CCUS plays a larger role across all sectors in a 1.5°C scenario




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide.

**Relative to the 1.75°C scenario, gas CCUS is estimated to play a larger role across all sectors under 1.5°C.** Figure 7 shows gas CCUS uptake by application in a 1.5°C scenario over the period to 2050. There is a stronger role for low-carbon hydrogen production, a more rapid decarbonization of heavy industry, as well as a stronger role in power generation. $CO_2$ captured by gas CCUS with low-carbon hydrogen production roughly doubles relative to a 1.75°C scenario. While gas CCUS in industry could account for around 3 $GtCO_2$ by 2050 in both the 1.75°C and 1.5°C scenarios, deployment is accelerated under the more stringent temperature target, with 70 percent more $CO_2$ captured by 2040 under a 1.5°C scenario. $CO_2$ captured by gas CCUS in power generation also increases 60 percent relative to a 1.75°C scenario, to around 3 $GtCO_2$ in 2050 in a 1.5°C scenario. As with the 1.75°C scenario, although overall gas CCUS in industry plays a larger role than in power, in the early stages, gas CCUS in power is deployed more rapidly, due to the rapid pace of power sector decarbonization and the relatively low cost of gas CCUS in power.

**Improvements in $CO_2$ capture rates could also reduce barriers to deployment of CCUS on natural gas use.** Recent IEA Greenhouse Gas R&D Programme (IEAGHG) analysis suggests that strong improvements in $CO_2$ capture rates can be delivered for a moderate cost premium, unlocking the role of CCUS in a net zero emissions electricity system. Until recently, capture rates for CCUS technologies applied in power stations or industrial furnaces were estimated at 85–90 percent, but IEAGHG estimates that increasing capture rates from 90 percent to over 99 percent would only increase capture costs by 4 percent and 10 percent for coal- and gas-based power generation respectively.[18] The modeling carried out in this study included both 90 percent and 99 percent capture rate technologies, with a higher capture rate incurring a cost premium in line with this analysis.

**Renewable hydrogen may offset some gas CCUS demand in several sectors but its scope to displace it will be limited.** Renewable hydrogen could offset some natural gas CCUS demand in power, iron and steel, chemicals, and heavy transport. Although it is costly in many regions today, it is cost-competitive with low-carbon hydrogen in some regions with very large renewable resources and will fall in cost over time in line with falling renewables costs. The role of gas CCUS in power, industry, gas production, and low-carbon hydrogen production, identified in this study, takes expected reductions in the cost of renewable hydrogen into account. But more rapid reductions in the costs of renewable hydrogen could result in greater uptake of this technology and a smaller role for gas CCUS. However, renewable hydrogen is unlikely to displace gas CCUS entirely. First, CCUS can reduce process emissions associated with natural gas use, which account for a large share of total emissions in the cement and other industrial sectors. Second, gas CCUS will benefit from existing gas infrastructure, while shifting to renewable hydrogen at scale would require new infrastructure, extensive decentralized hydrogen production, or repurposing of existing gas infrastructure and a complete, sudden, disruptive, and costly complete scrapping of gas facilities before the end of their normal operating life. Third, while renewable costs are likely to continue to fall over time through innovation, availability of renewable resources for renewable hydrogen production may be constrained by the rapid growth in electricity production needed to meet growing electricity demand and electrification of heat and transport. Fourth, low-carbon hydrogen may remain cost-competitive in regions with cheap gas reserves and capacity to produce at scale.

**In both scenarios, using gas CCUS to meet climate goals requires that methane emissions from upstream and downstream natural gas are minimized.** The IEA estimates that around 41 Mt of methane were emitted from upstream and downstream natural gas operations in 2020. Methane is a powerful greenhouse gas, with a global warming potential of 28–36 over a 100-year time frame[19] Therefore, in a 100-year time frame, 2020 methane emissions carry a global warming potential equivalent to around 1.3 $GtCO_2$, or around 15 percent of the total contribution to global warming of natural gas production and use. Reducing methane emissions from upstream and downstream natural gas is therefore necessary to ensure gas CCUS contributes to achieving climate objectives. Consideration of methane emissions in this analysis aligns with the IEA's Sustainable Development Scenario, which sees emissions fall by 75 percent from 2020 levels to 10 Mt in 2040.



**The application of CCUS on natural gas could play a signficant role in achieving the objectives of the Paris Agreement Deployment, if countries continue to produce and use natural gas.** In this section, the role of gas CCUS in reaching global temperature targets was characterized. Gas CCUS can make a large contribution to achieving 2050 emissions in line with 1.75°C, particularly in industry, power, and hydrogen production. Switching to natural gas and deploying CCUS can reduce coal and oil use and associated emissions, particularly in industry. Failure to deploy CCUS on natural gas production and use could increase the cost of the transition or result in an inability to meet the temperature target. The contribution of gas CCUS is even larger in a 1.5°C scenario. While alternatives to gas CCUS exist in some circumstances, the technology is likely to play a significant role in the transition to net zero emissions. In the following sections, the key drivers of gas CCUS deployment in industry, power generation, hydrogen production, and gas production are considered, as well as how its role could vary geographically.



18 IEA GHG (2019): Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass.

19 This signifies that 1 kilogram of methane contributes 28–36 times more warming than the same quantity of carbon dioxide.

### Box 3. The role of CCUS on natural gas-based industry: Key messages

- CCUS is one of the few solutions that can address process emissions from natural gas use in industry as well as emissions from fuel combustion. Where natural gas is used for high-temperature heat or as a chemical feedstaock with associated process emissions, CCUS, along with clean hydrogen, are considered the most economically viable, and in some cases, the only mitigation option available.
- The expected need for CCUS on natural gas use in industry will vary by country, depending on the affordability of gas relative to alternative fuels, the stringency of national climate commitments, and the relative importance of sectors (such as chemicals) best suited to gas CCUS. Where gas is readily available and affordable, it likely represents a larger share of the industrial energy mix, so the opportunity to decarbonize industry by deploying gas CCUS is greater. Further, gas CCUS is likely to play a greater role by 2050 in countries with strong climate commitments, such as a 2050 net zero emissions target.
- Scenario analysis as part of this study suggests significant deployment of CCUS in natural gas-based industry may be required to meet Paris Agreement targets. In a 1.75°C scenario, gas with CCUS could meet 30 percent of industrial energy demand by 2050; in a 1.5°C world, gas could meet a similar share of energy demand in 2050, but deployment could ramp up earlier to reduce emissions more aggressively.
- Analysis estimates that failure to deploy CCUS on natural gas use in industry could materially increase the costs of remaining on a 1.75°C pathway. The additional cost burden could be driven by the use of costlier oil-based CCUS in the chemicals sector, and electric heating technologies and coal with CCUS to provide high-temperature heat across manufacturing industries.

## 2.3 CCUS deployment on natural gas-based industry

**This section characterizes the application of CCUS in natural gas-based industry.** In this report, gas CCUS in industry refers to the use of CCUS to capture the $CO_2$ from natural gas used as a fuel in the industry sector, as well as any associated industrial process emissions. A further application of gas CCUS is to capture the $CO_2$ from natural gas used as a feedstock in hydrogen production (this application is considered separately in section 2.5). After outlining the rationale for gas CCUS in mitigating industrial $CO_2$ emissions globally, it estimates the potential role of industry gas CCUS in meeting a 1.75°C climate objective, drawing on a cost-optimized energy scenario developed for this study. It also identifies key factors behind the regional variation of industry gas CCUS. Finally, it discusses the potentially increased contribution of industry gas CCUS in a 1.5°C scenario.

**$CO_2$ emissions from industry account for around 17 percent of the world's total emissions and are projected to grow under current policies.** In 2019, $CO_2$ emissions from industry were around 5.8 $GtCO_2$, or 17 percent of the 33 $GtCO_2$ total energy-related $CO_2$ emissions. Under current policies, $CO_2$ emissions from industry are projected to continue to grow: the IEA Stated Policies Scenario projects growth of 12 percent to 6.5 $GtCO_2$ over the next two decades.

**CCUS is one of a small number of solutions to decarbonize high-temperature industrial heat produced using natural gas.** High-temperature heat is required across the industrial sector, including in iron and steel, non-metallic minerals, cement, and chemicals. Natural gas with CCUS is particularly suited to producing the high-temperature heat required in these sectors, which is difficult to electrify.[20]

**Further, CCUS is one of the few solutions that can address process emissions as well as emissions from fuel combustion.** Decarbonization of the non-metallic minerals sector, including cement, is further complicated by the large share of process emissions in total $CO_2$ generation (accounting for over 65 percent of emissions in the sector, according to the IEA).[21] These emissions

20 McKinsey (2018): https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.pdf.

21 IEA (2020): https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry.



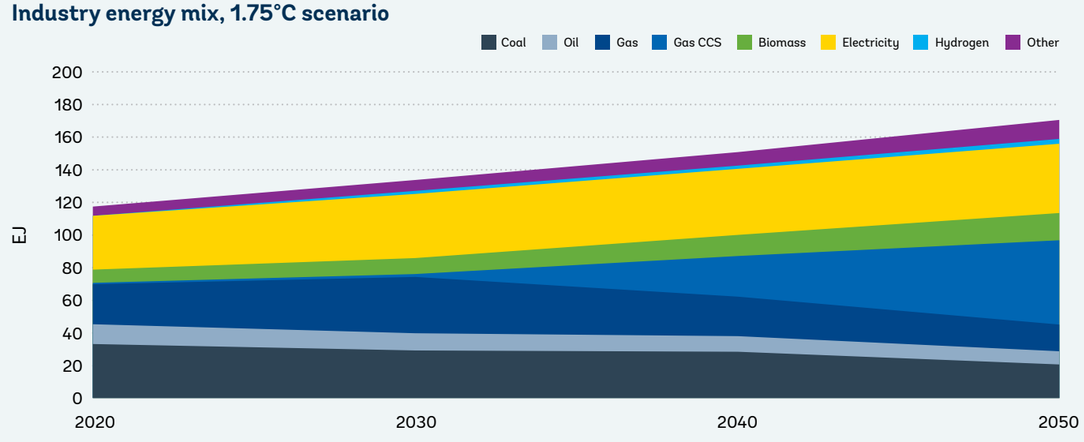
are inherent in the chemistry of cement production and therefore cannot be avoided by electrification. Although coal is the dominant fuel in non-metallic minerals production, gas is also used. Overall, gas accounts for almost 20 percent of fuel used in this sector, and much more than that in Australia (60 percent) and the United States (57 percent). Analysis undertaken in this study suggests CCUS could capture up to 0.2 $GtCO_2$ of natural gas-based cement emissions, or 7 percent of the 3 $GtCO_2$ captured through the use of gas CCUS in the industry sector.

Gas CCUS could satisfy 30 percent of industrial energy demand by 2050 in a 1.75°C scenario. Figure 8 shows the industry energy mix estimated under a 1.75°C scenario developed in this study over the period to 2050. Industrial energy demand grows by over 45 percent by 2050, reaching around 175 exajoules (EJ)/year by mid-century. Gas with CCUS could provide over 50 EJ by 2050, equivalent to 30 percent of the industrial energy mix. Unabated gas use falls over the same period, with its share in the industrial energy mix decreasing from 20 percent today to around 10 percent in 2050. Shares of electricity and biomass in the energy mix remain broadly flat over the next 30 years, as decarbonized gas abates an increasing proportion of industry emissions. Coal and oil provide a decreasing proportion of industrial energy, as they are displaced by gas with CCUS.

### Box 4. Capturing carbon at the Emirates Steel plant in Abu Dhabi

CCUS at the Emirates Steel production facility captures 0.8 $MtCO_2$ per year. The world's first commercial iron and steel CCUS facility, the Al Reyadah Project, is capable of capturing, transporting, and storing up to 0.8 $MtCO_2$ per year. The $CO_2$ is captured from flue gas released during gas-powered steel production and transported to nearby oil fields for use in enhanced oil recovery. The project began in 2016 with support from the government of the United Arab Emirates, as part of a wider package to deliver the world's first zero-carbon sustainable city.[22]

**Figure 8. Gas with CCUS dominates the industry energy mix by 2050 in a 1.75°C scenario**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: Figure shows energy use only; additional hydrogen used in production of ammonia and methanol is taken into account in Section 2.5: Gas CCUS for low-carbon hydrogen production. CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

22 MIT (n.d.): https://sequestration.mit.edu/tools/projects/esi_ccs.html.

**Gas CCUS is particularly suited to the chemicals sector and other sectors where there is the opportunity to shift away from coal.** The role of gas, coal, and oil varies across industries. Coal plays the largest role in the iron and steel sector, where it accounts for around 85 percent of fossil fuel use, and in the non-metallic minerals sector (including cement, glass, and ceramics), where it accounts for around 70 percent of fossil fuel use. In the chemicals sector and elsewhere, coal plays a much smaller role, accounting for around 33 percent of fossil fuel use in chemicals, and under 25 percent in all other sectors. As a result, growth in gas, and gas CCUS, is driven by the lower $CO_2$ intensity of gas and lower residual emissions from gas CCUS in sectors (such as chemicals) where it is easier to shift away from coal.

**The expected need for CCUS on natural gas use in industry will vary by country, depending on the affordability of gas relative to alternative fuels, the stringency of national climate commitments, and the relative importance of sectors (such as chemicals) best suited to gas CCUS.** Where gas is readily available and affordable, it likely represents a larger share of the industrial energy mix, so the opportunity to decarbonize industry by deploying gas CCUS is greater. Further, gas CCUS is likely to play a greater role by 2050 in countries with strong climate commitments, such as a 2050 net zero emissions target. Finally, countries with a strong role for industry sectors (such as chemicals) that are less suited to coal are likely to require CCUS to decarbonize industry on the path to net zero, given that there are limited alternative solutions to reducing emissions in these sectors.

**Gas CCUS could play the strongest role in large gas users such as the Middle East, Canada, and the United States, accounting for around 40–60 percent of the industry energy mix in 2050.** Figure 9 shows the industry energy mix in key modelled regions in the 1.75°C scenario developed in this study. The five regions with the strongest role for gas CCUS in industry are all large gas users. The contribution of gas CCUS to the industry energy mix in 2050 could be around 60 percent in the Middle East, and 40 percent in Canada and the United States. While the large role of gas CCUS in these regions is strongly driven by the availability and affordability of natural gas, in the Middle East it is also driven by the low share of industrial sectors that are typically fuelled with coal, which account for around 10 percent of industrial fuel use.

**Conversely, gas CCUS could play a more moderate role in constrained gas users such as India, China, Japan, and Korea, accounting for 10–30 percent of the industry energy mix in 2050.** The contribution of gas CCUS to the industry energy mix in 2050 could be around 20–30 percent in China, Japan, and Korea (though it should be noted that in the case of China this represents a very large gas CCUS opportunity in absolute terms, due to the large size of its economy and its energy system). In India, where gas accounts for only 3 percent of industrial gas use today, the contribution could be smaller still, at around 10 percent of the industry energy mix in 2050.

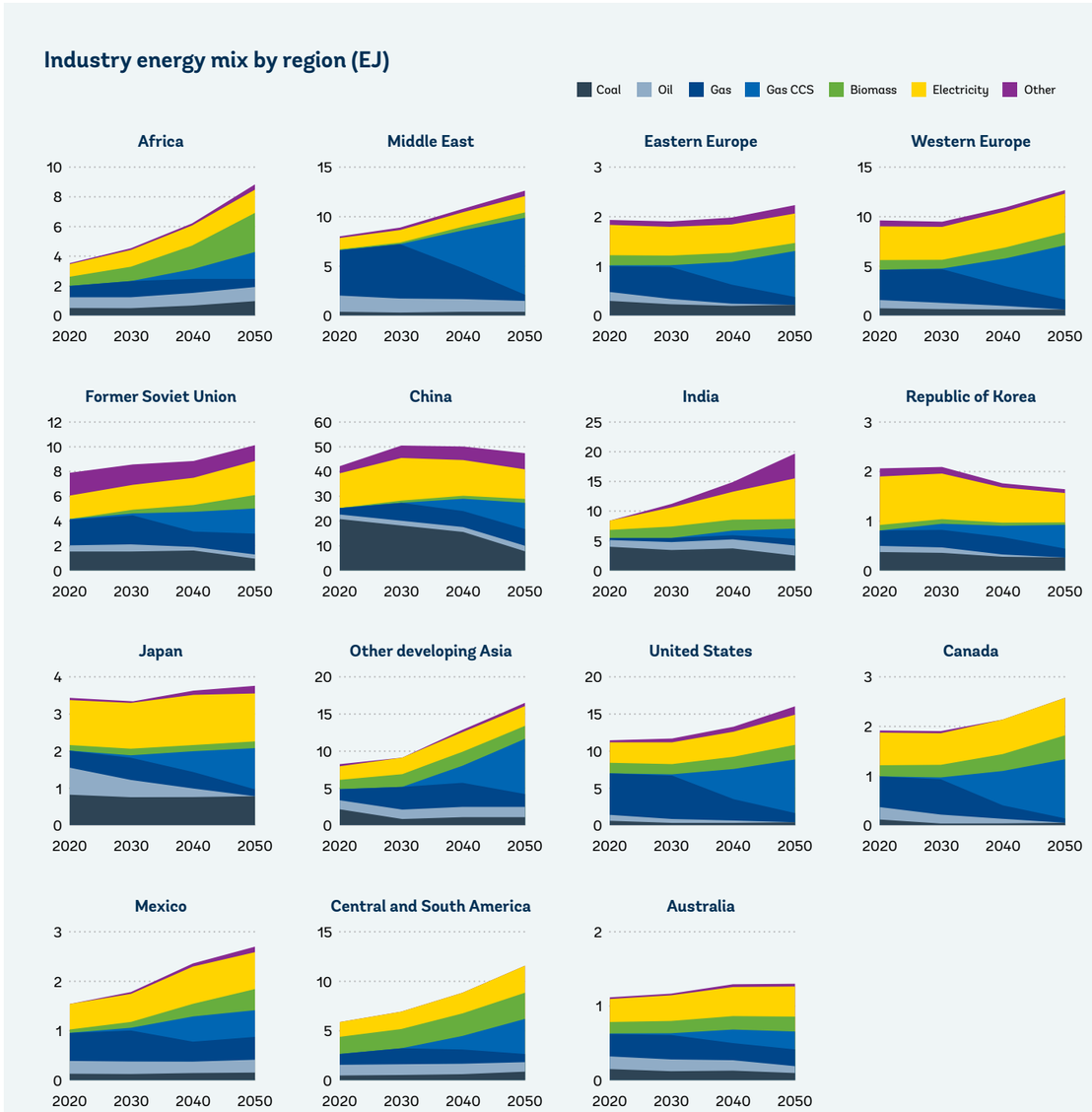
**Finally, the stringency of domestic climate commitments is likely to increase the need for CCUS on natural gas use in industry.** In the 1.75°C scenario modelled in this study, gas CCUS plays a still smaller role in gas exporters and large gas users (the former Soviet Union, Mexico, and Australia) than in constrained gas users (Japan and Korea). The difference in the role of gas CCUS in these sectors is driven by the difference in climate commitments. While, at the global level, net zero $CO_2$ emissions are achieved around 2070 in this scenario, a number of countries (including Japan and Korea) have set net zero targets for 2050 and achieve net zero emissions in advance of the 2070 average, while countries and regions that have not set net zero targets would achieve net zero beyond 2070. Because of constrained gas users' more ambitious climate commitments, gas CCUS plays a stronger role in industry in 2050 in these countries than it does in some gas exporters and large gas users.[23]

**Analysis estimates that failure to deploy CCUS on natural gas use in industry could materially increase the costs of remaining on a 1.75°C pathway.** As discussed in Section 2.2, a failure to deploy gas CCUS could increase the costs of achieving a 1.75°C pathway by around $400 billion in 2050, relative to the scenario with gas CCUS included. As industry accounts for around 65 percent of total gas CCUS, a similar proportion (e.g., around $220 billion) could be borne in this sector. The additional cost burden could be driven by the use of costlier oil-based CCUS in the chemicals sector, and electric heating technologies and coal CCUS to provide high-temperature heat across manufacturing industries.

23 Since this analysis was completed, Australia has set a net zero emissions target. If this commitment is met, the role of gas CCUS in industry is likely to increase relative to the levels set out in this scenario.



Figure 9. The regional role of gas CCUS in industry will vary with its availability and the role of energy-intensive industry

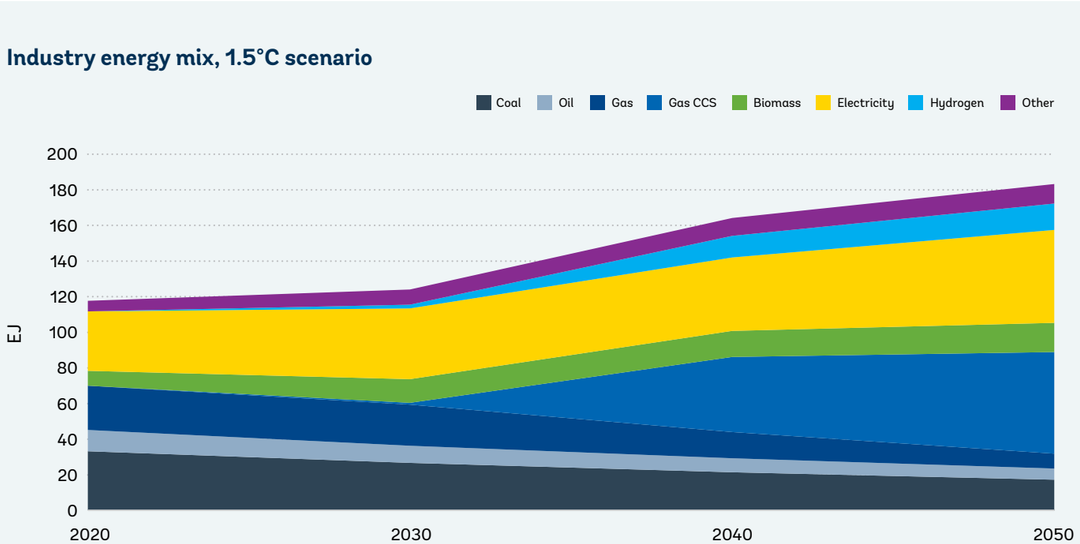



Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: The regions listed here are represented in the TIAM-Grantham Energy System Model used in this study and differ from the World Bank's classification of world regions

**Uptake of gas CCUS in industry could ramp up sooner in a 1.5°C scenario, meeting a similar level of energy demand around 10 years earlier than in a 1.75°C scenario.** Figure 10 shows the global industry energy mix in a 1.5°C scenario over the period to 2050. Industry energy demand increases around 50 percent by 2050. Gas CCUS uptake in industry in a 1.5°C scenario ramps up sooner than in a 1.75°C scenario, meaning cumulative emissions stored over the period are increased despite representing a similar share of the industry energy mix by 2050. The more urgent need to reduce emissions in a 1.5°C scenario results in gas CCUS playing a stronger role by 2040, accounting for 70 percent more of the industry energy mix than in a 1.75°C scenario. By 2050, gas CCUS in industry plays a similar role to the 1.75°C scenario, reaching just over 30 percent of industrial energy demand by 2050.

**The deployment of CCUS is a key decarbonization option for natural gas-based industry in both the 1.75°C and 1.5°C scenarios.** This section estimates the need for gas CCUS as a mitigation option for industry in meeting climate objectives. CCUS is likely to be an important technology to decarbonize industry due to the sector's large contribution to $CO_2$ emissions and the difficulty in reducing $CO_2$ emissions through electrification. As a result, gas CCUS could potentially provide up to 30 percent of industrial energy demand by 2050 in both the 1.75°C and 1.5°C scenarios. The role of gas CCUS in industry is likely to be highest in large gas users and gas exporters with large sectors such as chemicals) that are less suited to coal, such as the Middle East, Canada, and the United States. Meanwhile, it will be more limited in constrained gas users with small cement and chemicals sectors, such as Japan, Eastern Europe, and many African nations. Failure to deploy gas CCUS in industry could materially increase the cost of meeting a 1.75°C temperature target, accounting for over half of the additional $400 billion cost of achieving the target without gas CCUS. Subsequent sections summarize the role of gas CCUS in power generation and other key applications.

**Figure 10. In a 1.5°C scenario, large-scale deployment of gas with CCUS in industry ramps up sooner**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: Figure shows energy use only; additional hydrogen used in production of ammonia and methanol is taken into account in section 2.5: Gas CCUS for low-carbon hydrogen production. CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.



## 2.4 CCUS on gas-based power generation

### Box 5. The role of CCUS on gas-based power generation: Key messages

- **In countries where low-cost natural gas is available, deploying CCUS on gas power generation may reduce the costs of fully decarbonizing the electricity grid.** To reduce the costs of maintaining reliable electricity supply, renewables and battery storage may need to be complemented with alternative sources of firm and dispatchable low-carbon capacity, such as reservoir hydropower or clean hydrogen. In regions with low-cost natural gas supply, natural gas power generation with CCUS may also be used to provide firm, dispatchable, synchronous low-carbon power to complement large penetrations of variable renewables.
- **As with industry, opportunities for gas CCUS in power will be partly driven by the accessibility and affordability of natural gas.** Gas CCUS could play the strongest role in power generation in large gas users with very low domestic gas prices, such as the Middle East and the United States, accounting for around 15–25 percent of the generation mix in 2050. Conversely, gas CCUS could play a minimal power generation role in constrained gas users such as Japan, India, and Korea.
- **The role of conventional firm low-carbon generation (nuclear and hydro) in the national generation mix will also determine how much gas CCUS is needed to balance supply and demand.** Gas CCUS will tend to play a stronger role in countries where there is limited contribution from nuclear and hydropower—conventional firm low-carbon generation technologies—in the generation mix. For example, gas CCUS could play a greater role in power generation in constrained gas users in Africa than large gas user Canada, due to the relative contribution of nuclear and hydropower in the generation mix.
- **Analyses undertaken as part of this study estimate that CCUS on gas power generation may play a small but important role in decarbonizing power generation.** In a 1.75°C scenario, natural gas with CCUS could provide around 10 percent of power generation by 2050; in a 1.5°C scenario, gas CCUS could provide almost 15 percent of generation as more ambitious climate targets drive earlier deployment.
- **Hydrogen could potentially substitute for gas CCUS in some regions if costs fall more rapidly than foreseen.** Hydrogen is more likely to substitute for gas CCUS in regions facing high gas costs, and with low-cost renewable resources or favorable access to lower-cost clean hydrogen imports.

This section describes in detail the potential need for CCUS deployment on natural gas power generation. It sets out the potential application of gas CCUS in mitigating $CO_2$ emissions from power generation globally, and summarizes estimated gas CCUS in power generation in meeting a 1.75°C climate objective. It discusses key drivers of potential variation in the role of gas power CCUS and identifies regional patterns in deployment over the period to 2050. Based on this evidence, it discusses the cost implications of deployment of gas CCUS in power generation. Finally, it estimates the potential role gas CCUS in electricity generation could play in a 1.5°C scenario.

$CO_2$ emissions from power generation account for over 40 percent of the world total, and are projected to largely persist under current policies. In 2020, $CO_2$ emissions from power generation were around 13.5 $GtCO_2$, or 40 percent of the 32 $GtCO_2$ total energy-related $CO_2$ emissions. Under current policies, $CO_2$ emissions from power generation are projected to fall only slightly: the IEA's Stated Policies Scenario projects that $CO_2$ emissions will fall by 9 percent to 12.5 $GtCO_2$ over the next two decades.[24]

Renewables with battery storage are likely to provide the majority of electricity in a decarbonized electricity system, but electricity system reliability may require additional firm and dispatchable

24 IEA's World Energy Outlook 2020.

### Box 6. The role of firm, dispatchable, and synchronous technologies in power generation

Wind and solar are variable renewables, signifying that their output depends on weather conditions. As a result, while variable renewables alone can meet a significant share of electricity demand, they must be complemented with additional sources of low-carbon generation that are:

- **Firm**, signifying that they can generate when needed with a very high degree of confidence.
- **Dispatchable**, signifying that they can be operated flexibly and ramp output up or down to balance shortfall or surplus from variable renewables.
- **Synchronous**, signifying that they contribute to grid inertia through the energy provided by the rotating mass of the turbines they power. Grid inertia is needed to ensure that the frequency of the electricity system can be maintained in the event of an unforeseen generator outage.

Battery storage, combined with variable renewables, can provide firm and dispatchable capacity to a degree. These technologies can also provide "synthetic inertia," which can help restore the frequency of the electricity system following a generator outage, though they cannot slow the initial fall in frequency. However, at very high levels of output, renewables require large volumes of supporting battery storage to store a large share of excess output for use at times of excess demand, resulting in high costs of meeting demand.

To reduce the costs of maintaining reliable electricity supply, renewables and battery storage could be complemented by alternative sources of firm and dispatchable capacity.[25] Gas CCUS, reservoir hydropower, hydrogen, and nuclear are all firm generation technologies. Further, unlike nuclear, gas CCUS, hydropower, and hydrogen are also dispatchable.

Finally, unlike battery storage, nuclear, gas CCUS, hydro, and hydrogen are also synchronous. Some mix of these technologies will be needed to maintain grid inertia at required levels, to contain the initial fall in frequency following a generator outage.

low-carbon generation such as nuclear, hydropower, gas CCUS, and hydrogen. Renewables have experienced extremely strong cost reductions over the last two decades: recent analysis indicates that the cost of solar photovoltaic (PV) fell by 85 percent and the cost of wind by 70 percent between 2010 and 2020.[26] Further cost reductions are highly likely as deployment of these technologies increases. The IEA predicts that in a 1.5°C scenario, solar PV costs could fall 63 percent by 2050, while offshore and onshore wind costs could fall 63 percent and 14 percent over the same period, respectively.[27] However, there are limits to the ability of variable renewables such as wind and solar to cost-effectively meet electricity demand in full (Box 6).

**Detailed electricity system modelling was carried out to analyse the potential role of gas CCUS in the future generation mix across multiple national electricity systems.** The deployment of gas CCUS in a decarbonized electricity system will be determined by the hour-by-hour variation in electricity demand, output of variable renewables, and the relationship between the two. Detailed electricity system modelling is needed to adequately characterize the role of gas CCUS at hourly resolution. To characterize the role of gas CCUS in the future generation mix across the 15 major countries and wider regions considered here, this study modelled four archetypal electricity systems that span the range of output of variable renewables and the variation in electricity demand that are expected to determine the role and value of CCUS. These archetypal electricity systems are shown in Figure 11 and described below.

25 Cost reductions in battery technology, along with cost reductions in renewable energy, CCUS, etc. are considered in the modelling assessment, covering the time horizon 2020–2100. Furthermore, modelling carried out for this study indicates that volumes of battery storage needed to achieve 100% renewables given seasonal variation are cost-prohibitive.
26 Lazard (2020): https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/.
27 IEA (2021):.Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net).



- **R1—year-round cooling**—is most often used in equatorial or tropical regions with minimal demand for space heating, and high demand for cooling with little seasonal variation. R1 regions are also characterized by high solar PV capacity factors. Examples include Indonesia and Brazil.
- **R2—seasonal cooling**—represents subtropical or regions with low demand for space heating, and high seasonal demand for cooling. R2 regions are also characterized by high solar PV capacity factors. Examples include Mexico and Australia.
- **R3—seasonal heating**—is found in temperate regions with significant demand for space heating, and low seasonal demand for cooling. R3 regions are characterized by lower solar PV capacity factors and higher wind capacity factors. Examples include the United Kingdom and Germany.
- **R4—high seasonal heating**—represents colder temperate or subpolar regions with very significant demand for space heating, and no seasonal demand for cooling. R4 regions are characterized by very low solar PV capacity factors and higher wind capacity factors. Examples include Canada and Kazakhstan.

Analysis estimates that gas CCUS could provide up to 10 percent of power generation by 2050 in a 1.75°C scenario. Figure 12 shows the world generation mix in the 1.75°C scenario developed in this study. Over the period to 2050, electricity demand increases by more than 60 percent, while coal, oil, and unabated gas generation decrease by more than 95 percent; and low-carbon generation (defined as renewables, nuclear, and gas CCUS) increases by a factor of four. Over this period gas CCUS emerges as a small but increasingly important source of low-carbon generation, accounting for around 8 percent of total generation in 2040 and 10 percent in 2050.

**Gas CCUS is substantially cheaper than coal CCUS for new plants.** Coal CCUS is not part of the least-cost mix according to the modelling carried out in this study. Although coal is generally cheaper than gas in many regions, coal CCUS carries a substantial capital cost premium over gas CCUS. IEAGHG estimates the cost of coal CCUS at $2,400–2,650 per kilowatt (kW), gas CCUS at $1,500–1,600 per kW; similarly, IEAGHG estimates the efficiency of a coal CCUS plant at 33–36 percent, and a gas CCUS plant at 44–45 percent.[28]

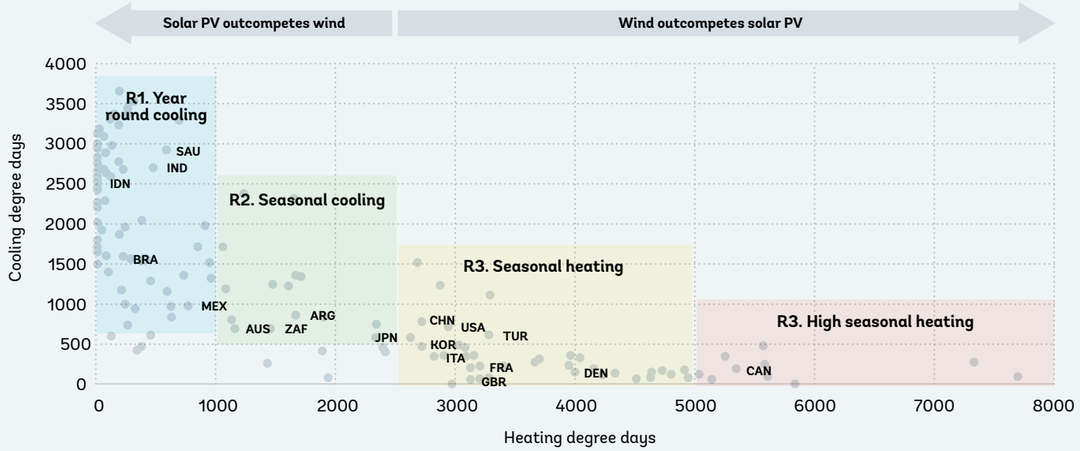
### Box 7. Capturing carbon at the Caledonia Power Plant in Scotland, United Kingdom

**The Caledonia Clean Energy project in Scotland aims to capture 3 $MtCO_2$ per year by the mid-2020s.** The 1.3 gigawatt gas power plant under development in Grangemouth, central Scotland, is expected to capture 3 $MtCO_2$ per year by the early to mid-2020s. The captured carbon is set to be transported to the North Sea, where it will be reinjected into geological formations for dedicated long-term storage, making use of existing oil and gas industry infrastructure. The project aims to deliver low-carbon gas power to support the growing share of renewably generated electricity in the United Kingdom, ensuring grid stability as unabated fossil fuels are phased out entirely. A recent feasibility study determined that the project could generate £1 billion in gross value added for the British economy during the 2020–23 construction phase and deliver cost-competitive electricity to the grid when operational.[29]

**Gas CCUS is estimated to play a relatively similar role across different climates and patterns of seasonal demand.** The four archetypal decarbonized electricity systems covering different climate types are modelled on an hour-by-hour level to understand the role of gas CCUS in the future generation mix across multiple national electricity systems. The objective of the archetypal systems is to estimate the potential role of gas CCUS across two major drivers of variation: the profile of climate-driven seasonal demand variation, and the mix of variable renewables best suited to geographies. Figure 13 identifies the generation mix that could meet electricity demand at least cost across the four archetypal regions modelled in this study under moderate gas prices, defined as gas prices around $6/million British thermal units (MMBtu). Moderate gas prices are seen in countries such as Germany and the United Kingdom, which meet a substantial share of gas demand through imports and are well connected to gas exporters through pipelines. Figure 13 shows that the contribution of gas CCUS to a least-cost generation mix lies between 10–20

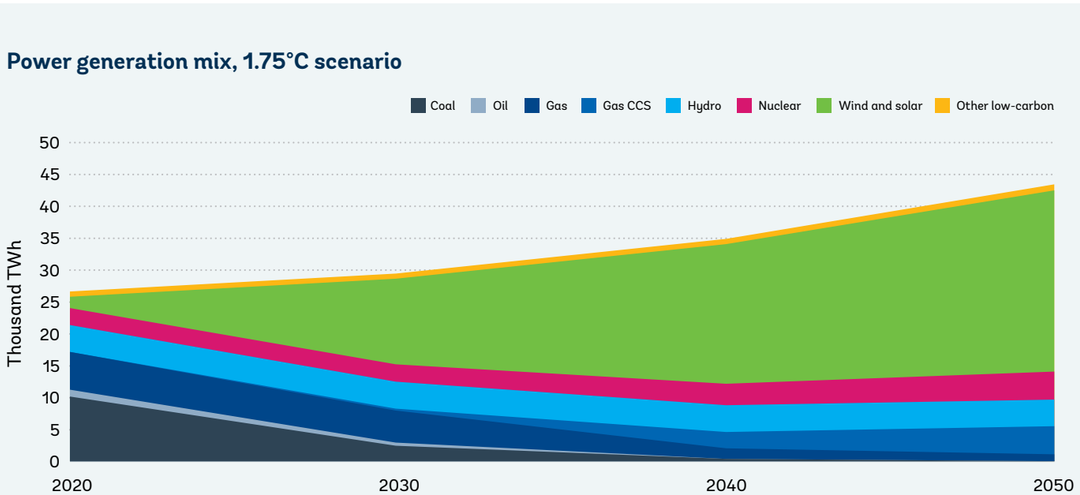
28 IEAGHG (2019): https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/951-2019-02-towards-zero-emissions.
29 Summit Power Caledonia UK Ltd (2018): https://summitpower.com/projects/carbon-capture/.

**Figure 11. Four archetypal power systems cover a range of renewable resource quality and seasonal demands**




Source: KAPSARC Global Degree-Days Database.
Note: PV = photovoltaic; Argentina (ARG); Australia (AUS); Brazil (BRA); Canada (CAN); China (CHN); France (FRA); Germany (DEU); India (IND); Indonesia (IDN); Italy (ITA); Japan (JPN); Republic of Korea (KOR); Saudi Arabia (SAU); South Africa (ZAF); Turkey (TUR); United Kingdom (GBR); United States (USA).

**Figure 12. Worldwide, gas CCUS could provide around 5% of power generation by 2050 in a 1.75°C scenario**



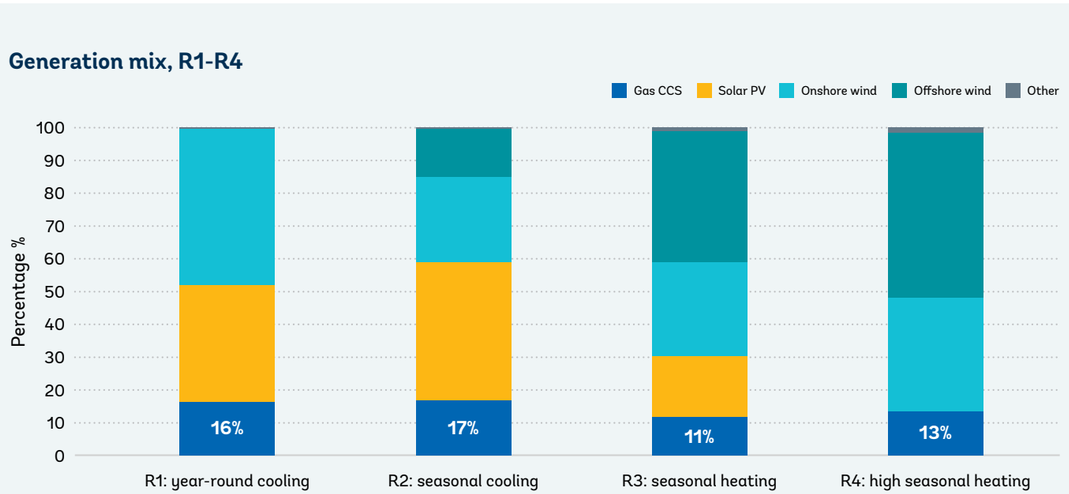

Source: Original compilation using the Imperial College WeSIM and TIAM-Grantham models.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.



percent of generation. Despite the benefit of gas CCUS in meeting swings in seasonal electricity demand, Figure 13 indicates that the profile of climate-driven seasonal demand variation is not a strong determinant of the role of gas CCUS. This is because, in a decarbonized electricity system with a high share of renewables, further increasing the share of renewables in the generation mix would entail deploying battery storage with increasingly lower utilization. Even where seasonal demand variation is minimal, the modelling suggests that once the share of variable renewables approaches 80 percent the large quantity of storage needed to balance this additional supply with demand imposes large costs, and gas CCUS emerges as a cost-competitive alternative, as demonstrated in Figure 14.

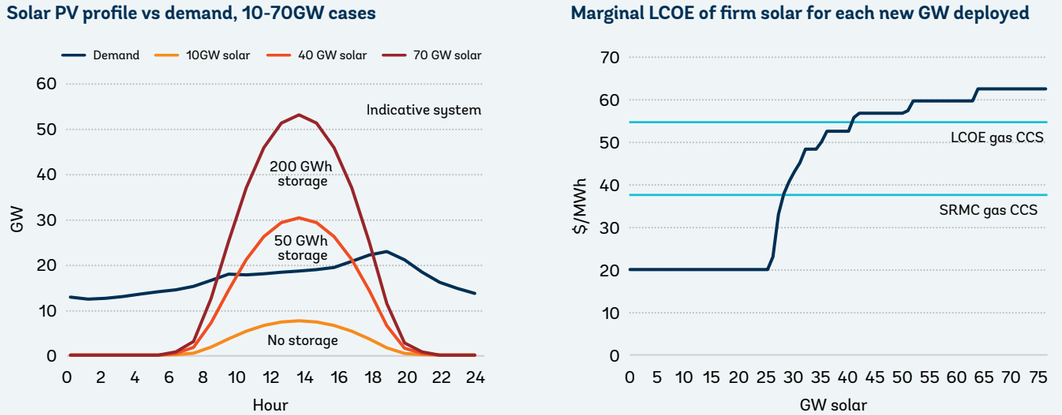
**In power systems with very high levels of variable renewables, gas CCUS can offer cost savings.** Renewables paired with battery storage can reliably meet a large share of electricity demand. However, the larger the share of renewables in the electricity mix, the larger the volume of battery storage needed to balance supply and demand. Figure 14 shows how the volume of battery storage needed to balance supply and demand increases with deployment of renewables, and how, at high levels of renewables gas, low-carbon power generation using natural gas with CCUS can emerge as a cost-effective alternative. The left-hand panel shows, for an indicative power system, the volume of battery storage needed to balance supply and demand with low, moderate, and high levels of solar PV on an average day. With low levels of solar PV, no battery storage is needed, as PV output is always below demand. With moderate levels of solar PV, some battery storage is needed, as demand is inadequate to absorb a small share of the PV when at peak output. With high levels of solar PV, substantially more battery storage is needed, as demand is inadequate to absorb a large share of the PV output. The right-hand panel shows the resulting levelized cost of electricity of firm solar (solar plus storage) as the volume of solar PV increases. Although the short-run and levelized costs of gas CCUS are substantially above the levelized cost of solar, they are lower than the levelized cost of firm solar (solar with battery storage) once solar PV reaches high levels.

**Figure 13. Gas CCUS could account for 10–20% of generation in 2050, in a 1.75°C scenario**



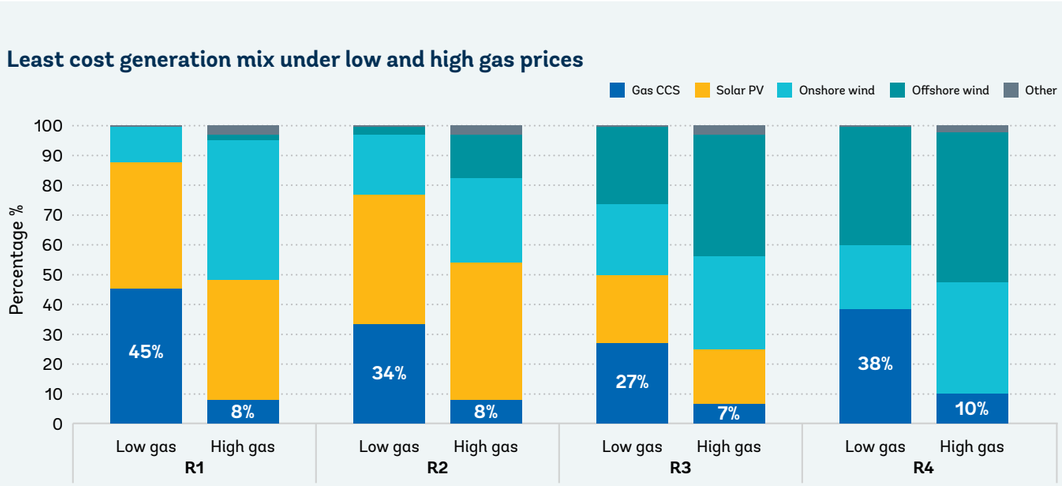

Source: Original compilation using the Imperial College WeSIM model.
Note: "Other" consists of hydrogen produced from renewables, as well as small volumes of bioenergy with carbon capture and storage (BECCS) to offset residual emissions from gas CCUS.
CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.

**Figure 14. Gas CCUS can offer cost savings in power systems with very high levels of variable renewables**




Source: Original compilation using the Imperial College WeSIM model.
Note: Gas CCUS costs estimated for $6/MMBtu gas. CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; LCOE = levelized cost of energy; SRMC = short-run marginal cost; PV = photovoltaic.

**Figure 15. The role of gas CCUS in power will be strongly driven by regional gas prices (2050)**




Source: Original compilation using the Imperial College WeSIM model.
Note: "Other" consists of hydrogen produced from renewables, as well as small volumes of bioenergy with carbon capture and storage (BECCS) to offset residual emissions from gas CCUS. CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.



**The cost of gas will affect the level of gas CCUS deployment in a net zero emissions electricity system.** Figure 15 identifies the generation mix that could meet electricity demand at least cost across the four archetypal regions modelled in this study under different gas prices. It shows that, under high gas prices, defined as gas prices around $10/MMBtu, the contribution of gas CCUS to a least-cost generation mix is only around 7–10 percent of generation, or around 5–7 percentage points less than under moderate prices. High gas prices are seen in countries such as Japan and Korea that are highly reliant on higher-cost LNG for their gas supply. Conversely, under low gas prices (i.e., around $3/MMBtu), the contribution of gas CCUS to a least-cost generation mix could be 27–45 percent of generation, and around 16–29 percentage points more than under moderate prices. Low gas prices are seen in countries such as Canada, the United States, and Saudi Arabia, that have large domestic resources and do not need to incur the costs of imports.

**The role of conventional firm low-carbon generation (nuclear and hydropower) in the national generation mix will determine how much gas CCUS is needed to balance supply and demand.** Figure 16 identifies the generation mix that could meet electricity demand at least cost across the four archetypal regions modelled in this study in countries with a substantial share of nuclear or hydropower in their generation mix.

- Figure 16 shows that, with a substantial share (defined as a share of around 30 percent of generation) of nuclear in the generation mix, the contribution of gas CCUS to a least-cost generation mix is only around 7–10 percent of generation, or around 40–70 percent of the level needed without nuclear. Example countries in which nuclear makes up a major share of the generation mix include France (72 percent share) and Ukraine (53 percent).
- Figure 16 also shows that, with a substantial share (i.e., about 30 percent) of hydropower in the generation mix, the contribution of gas CCUS to a least-cost generation mix is only around 5–6 percent of generation, or around 40 percent of the level needed without hydropower. Example countries and regions in which hydropower makes up a major share of the generation mix include Canada (59 percent share) and Central and South America (55 percent).

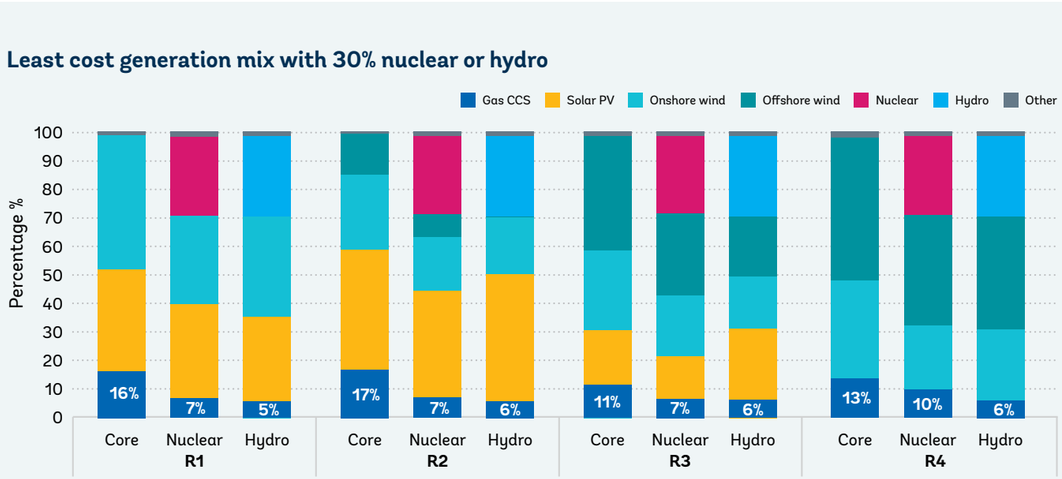
Gas CCUS is estimated to play the largest role in power generation in large gas users with very low domestic gas prices, such as the Middle East and the United States, accounting for around 15–25 percent of the generation mix in 2050. Figure 17 shows the generation mix in key modelled regions in the 1.75°C scenario developed in this study. Four of the five regions with the strongest role for gas CCUS in power generation are all large gas users. The contribution of gas CCUS to the power mix in 2050 could be around 26 percent in the Middle East, 19 percent in the former Soviet Union, 15 percent in the United States, and 11 percent in Australia. While the large role of gas CCUS in power generation in these regions is strongly driven by the availability and affordability of natural gas, in the Middle East and Australia it is also driven by the limited role of nuclear and hydropower in the generation mix, which together account for 14 percent of the mix in Australia and 6 percent in the Middle East.

**Conversely, gas CCUS could play a minimal power generation role in constrained gas users such as Japan, India, and Korea, and countries with abundant hydropower resources.** Modelling suggests gas CCUS may account for only 1–2 percent of generation in Japan and India, and 3–4 percent in Central and South America, Canada, and Korea. While the role of gas CCUS in Japan, India, and Korea is constrained by the poor availability and affordability of natural gas, in Japan and Korea it is also constrained by the availability of nuclear. In India, a tighter global climate target such as a 1.5°C target may be required to achieve net zero emissions electricity generation by 2050, which in turn would see an increase in the level of gas CCUS.[30] In Central and South America and Canada, the role of gas CCUS is constrained by the large role of hydropower.

**In some cases, the need for gas CCUS overrides availability and affordability as a driver.** For example, although Africa is a constrained gas user, the contribution of gas CCUS to the generation energy mix in 2050 could be around 12 percent.

30 The analysis uses capture rates below 100% (90% and 99% capture rates) and residual emissions in the gas supply chain. Taking these factors into account, gas CCUS can still play a significant role in the least-cost pathway to net zero. As with many areas of the economy, any residual emissions cannot be abated directly will need to be offset with negative emissions technologies such as CCUS. In this regard, the development of a CCUS network to address power and industrial emissions directly, provides synergies with negative emissions technologies such as BECCS and DACCS with the possibility of shared transport and storage infrastructure.

**Figure 16. The role of gas CCUS is smaller in the presence of substantial nuclear and hydro generation**




Source: Original compilation using the Imperial College WeSIM model.
Note: "Other" consists of hydrogen produced from renewables, as well as small volumes of bioenergy with carbon capture and storage (BECCS) to offset residual emissions from gas CCUS.
CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.

The limited role of nuclear and hydro in the generation mix, which together account for 18 percent of the mix, is likely to support a role for gas CCUS despite the relative limited availability and affordability of natural gas.

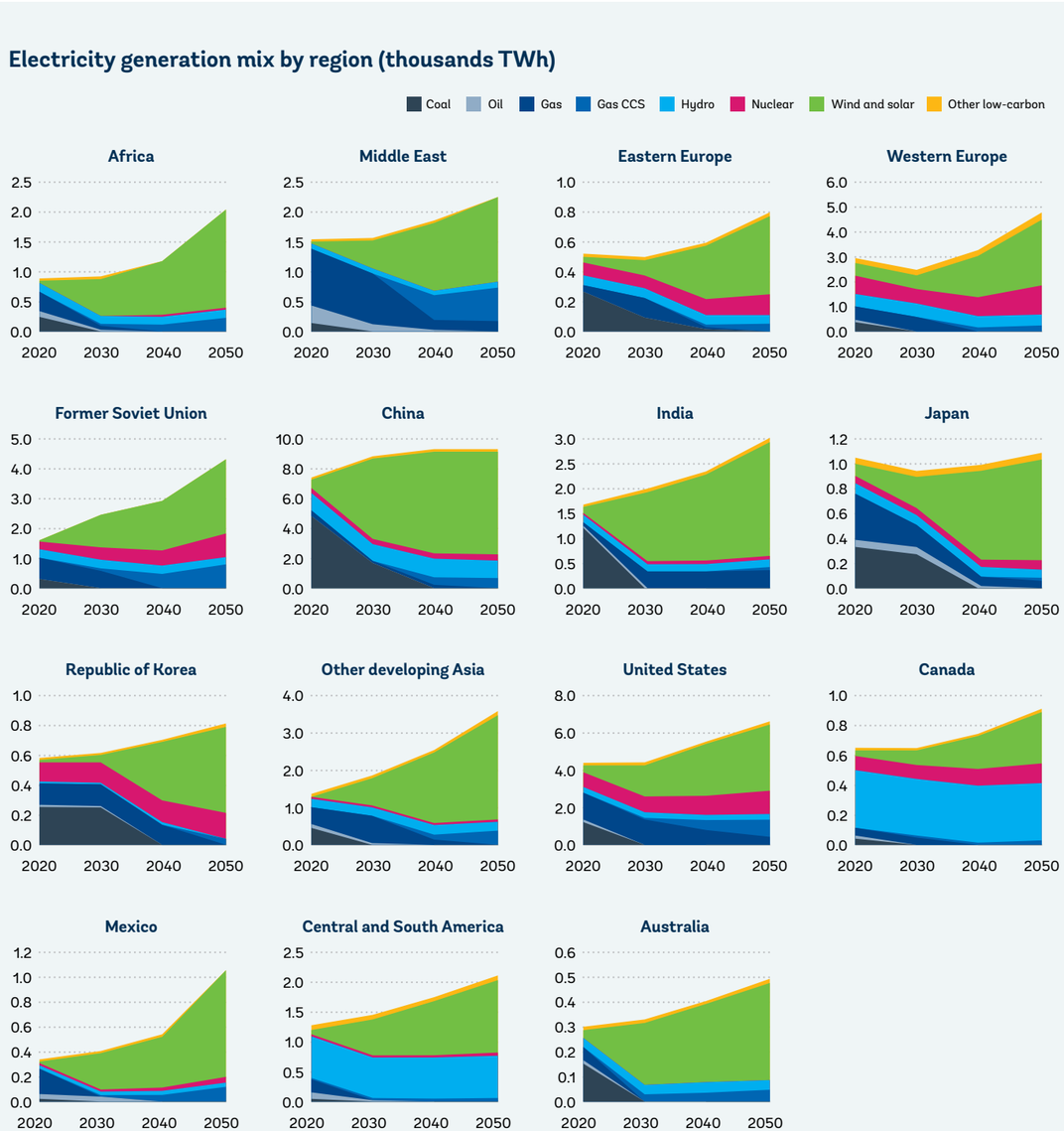
**Analysis estimates that not deploying CCUS on gas power generation could increase emissions from this sector by 1.2 $GtCO_2$ in 2050 or increase the cost of remaining on a 1.75°C pathway by around 10 percent.** Although gas CCUS is expected to play a relatively modest role in a 1.75°C scenario, contributing 10 percent of power generation in 2050, it is needed to reduce the costs of decarbonizing the electricity system. Around 25 EJ of gas, or around 20 percent of current gas demand, would be needed to achieve this level of generation; if, instead, unabated gas without CCUS were used to maintain the reliability of the electricity system, it would create around 1.2 Gt of additional $CO_2$ emissions. In order to achieve electricity system decarbonization without gas CCUS, more costly alternative solutions would be needed. Options include increasing deployment of nuclear, or overbuilding renewables, with the additional generation stored and shifted either with battery storage deployed at increasingly lower utilization rates, or through production of clean hydrogen and subsequent generation using hydrogen/ammonia generators. Modelling carried out for this study indicates that these solutions would increase the cost of power by around 10 percent.

**Gas CCUS could potentially play an increased role in a 1.5°C scenario, possibly providing as much as 15 percent of power generation by 2050.** Figure 18 shows the world generation mix in the 1.5°C scenario developed in this study. Over the period to 2050, unabated coal, oil, and gas generation fall rapidly to extremely low levels over the decade to 2030 before phasing out fully over the next three decades. As dispatchable unabated fossil generation is almost entirely phased out by 2050 in this scenario, gas CCUS emerges as the lowest-cost source of dispatchable low-carbon generation after hydropower, accounting for 11 percent of total generation in 2040 and 13 percent in 2050.

**Hydrogen could substitute for gas CCUS in some regions if costs fall more rapidly than foreseen.** Hydrogen is more likely to substitute for gas CCUS in regions facing high gas costs, and with low-cost renewable resources or favourable access to lower-cost clean hydrogen imports.

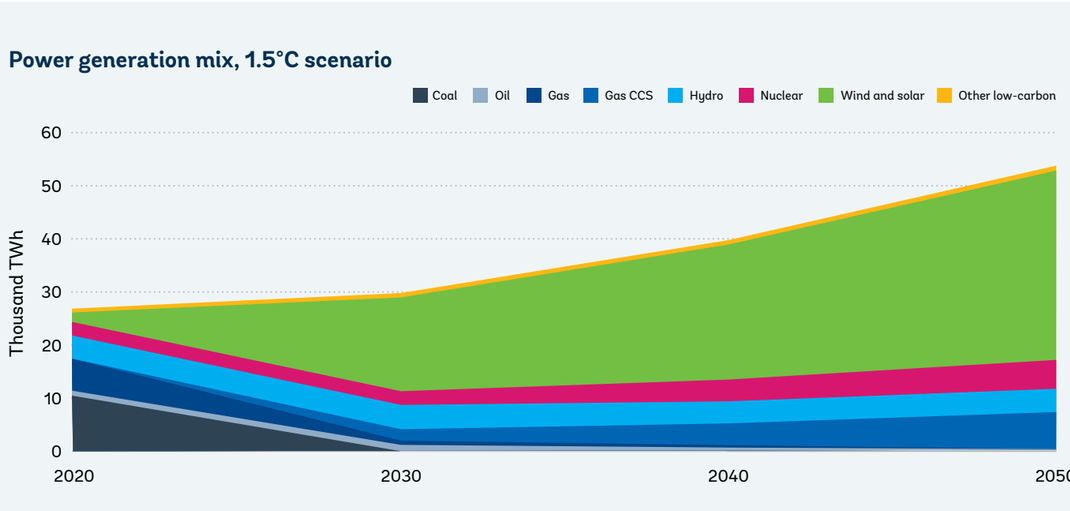


**Figure 17. The regional role of gas CCUS in power will vary, driven by gas prices and alternative firm power sources**



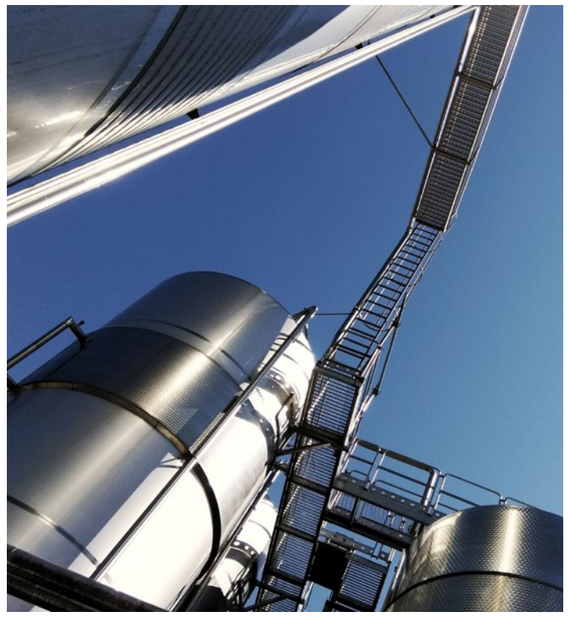

Source: Original compilation using the Imperial College WeSIM and TIAM-Grantham models.

**Figure 18. In a 1.5°C scenario, gas CCUS could provide 15% of power generation by 2050**




Source: Original compilation using the Imperial College WeSIM and TIAM-Grantham models.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

Natural gas CCUS will play a small but important role in decarbonizing power generation and achieving a 1.75°C or 1.5°C temperature target. This section has summarized the role of gas CCUS in power generation in 1.75°C and 1.5°C scenarios. CCUS plays a small but important role in decarbonizing power generation as a firm and dispatchable low-carbon generation technology. As a result, gas CCUS could provide around 10 percent of power generation by 2050 in a 1.75°C scenario and almost 15 percent in a 1.5°C scenario. The role of gas CCUS in power will be greatest in regions with both abundant supplies of low-cost gas and a relatively limited role for conventional firm low-carbon generation (nuclear and hydro), such as the United States, Africa, and Mexico; and more limited in regions with limited access to low-cost gas, and an important role for nuclear and hydro in the national generation mix, such as Japan, Canada, and Central and South America. Failure to deploy gas CCUS in power generation could either increase the cost of achieving a 1.75°C temperature target or decrease the likelihood of reaching that target. The next section considers the role of gas CCUS in low-carbon hydrogen production.





## 2.5 Gas CCUS for low-carbon hydrogen production

### Box 8. The role of gas CCUS in the production of low-carbon hydrogen: Key messages

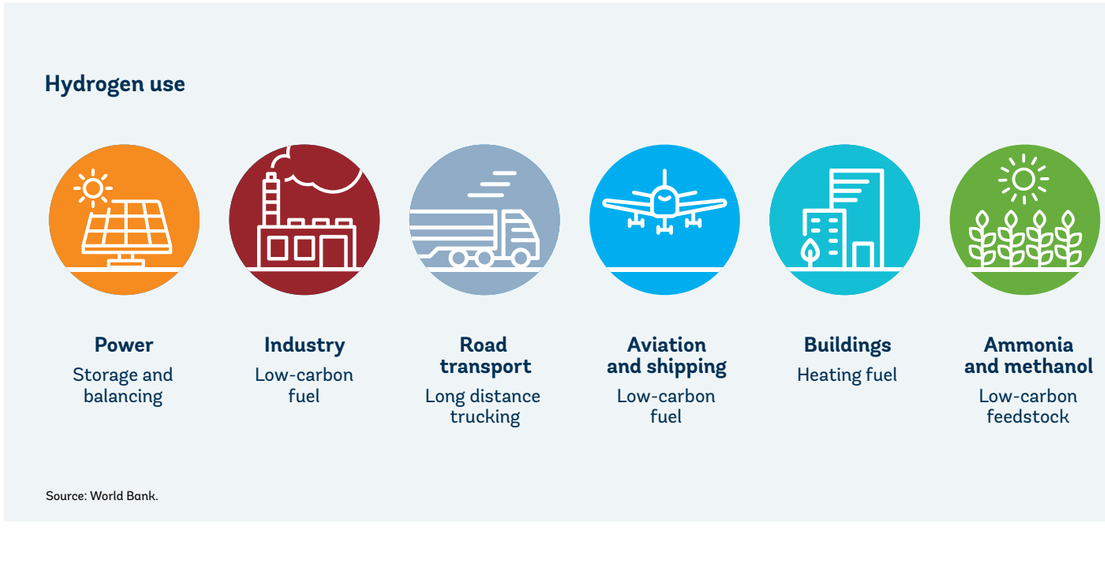
- While the specific contribution of low-carbon hydrogen to total clean hydrogen supply is highly uncertain, it is likely to play a valuable role in developing a clean hydrogen market. In the near term, low-carbon hydrogen is available to be rolled out at scale and at lower cost than renewable hydrogen, particularly in countries with abundant and cheap natural gas. While renewable hydrogen is expected to emerge as the main source of clean hydrogen as its costs decline, low-carbon hydrogen is likely to remain competitive in gas-rich regions.
- In particular, low-carbon hydrogen offers very low-cost CCUS opportunities in ammonia and methanol production. In these applications, the cost of shifting from gray to low-carbon hydrogen is typically around $25–35/t$CO_2$.
- The contribution of low-carbon hydrogen to total hydrogen supply will be strongly determined by the accessibility and affordability of natural gas. Low-carbon hydrogen is likely to play a greater role in large gas users and gas exporters, such as the United States and the Middle East, and particularly in countries where the renewable resources are relatively unexplored. In contrast, constrained gas users will either produce renewable hydrogen or source their clean hydrogen through imports.
- As a result, gas exporters could emerge as low-carbon hydrogen exporters, continuing to generate revenues from natural gas as use of unabated gas declines. Key exporters of low-carbon hydrogen could include Australia, Central Asia, Canada, and the Middle East, while key importers could include Japan and Korea.
- Overall, modelling suggests hydrogen could play a small but important role in achieving the Paris Agreement goals and net zero emissions. In the 1.75°C scenario modeled for this study, hydrogen produced from renewables (renewable hydrogen) and fossil fuels with CCUS (low-carbon hydrogen) together account for around 5 percent of final energy demand by 2050. In a 1.5°C scenario, hydrogen could provide around 10 percent of final energy demand as more ambitious climate targets drive earlier deployment. If policymakers favor this technology, or alternative technologies are slower to develop, hydrogen could play a more substantial role.

**This section assesses the deployment of CCUS in association with natural gas-based, low-carbon hydrogen production.** It summarizes the role of clean hydrogen in meeting a 1.75°C climate objective. It discusses the development of both renewable and low-carbon hydrogen and the potential contribution low-carbon hydrogen could make to total clean hydrogen supply. It discusses how the role of low-carbon hydrogen could vary by region. Finally, it estimates the role low-carbon hydrogen could play in a 1.5°C scenario.

**Hydrogen is a versatile fuel that could contribute to the decarbonization of many end-use applications when produced through a low-carbon process.** Low-carbon hydrogen can replace natural gas or other fossil fuels in a variety of sectors (Figure 19):

- In **power**, hydrogen could provide long-duration storage, balancing renewables output and demand over days, weeks, or months.
- In **industry**, hydrogen can be used in generators, furnaces, and boilers similar to those that currently use natural gas and can replace coking coal as a reducing agent to produce direct reduced iron.
- In **road transport**, hydrogen can be used with fuel cells and to power electric motors, avoiding the high cost, volume, and weight associated with batteries for long-distance trucking.
- In **aviation and shipping**, hydrogen can be used to produce low-carbon fuels, reducing the need for biomass and its associated risks of land use change in these sectors.
- In **buildings**, hydrogen can be used in boilers similar to natural gas boilers to provide heat.
- Finally, hydrogen is used as a **feedstock** in the production of ammonia and methanol, which are in turn used to produce transport fuels, fertilizer, and other chemicals.

**Figure 19. Hydrogen is a versatile solution across several different applications**

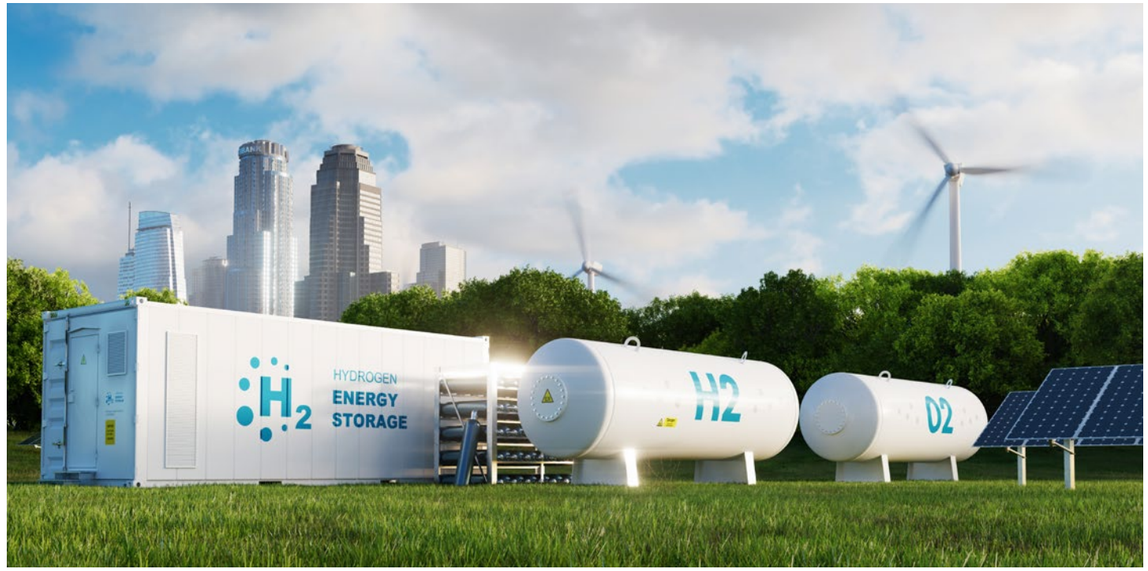



Source: World Bank.

### Box 9. Air Products' steam methane reformer, Port Arthur, United States

CCS at Air Products' steam methane reformer has captured and stored over 6 $MtCO_2$ since beginning operations in 2013. Air Products proposed the low-carbon hydrogen production project to the US Department of Energy in 2009, as part of the government department's Industrial Carbon Capture and Storage Program. Captured $CO_2$ is transported via pipeline to a nearby oil refinery, where it is used for enhanced oil recovery. The project employs a unique carbon capture method, vacuum swing adsorption, developed at speed for commercial deployment at the site.[31] The US Department of Energy invested $284 million in the project, covering two-thirds of the overall cost.[32]

**Hydrogen is estimated in this analysis to play a small but important role in a 1.75°C scenario, providing around 5 percent of final energy demand by 2050.** Figure 20 shows world clean hydrogen production in the 1.75°C scenario developed in this study. Over the period to 2050, hydrogen demand is estimated to grow relatively slowly initially, before ramping up rapidly by around 2040 and reaching around 25 EJ by 2050. Growth is slow initially as hydrogen production and end-use technologies take time to become cost competitive, and lower-cost climate solutions such as renewables are adequate to deliver much of the necessary emissions reductions. Initial growth is driven by opportunities to decarbonize industry, while later growth is driven by decarbonization of the transport sector. While overall volumes are small outside of current uses as an industry and refining feedstock, hydrogen plays an important role in transport, accounting for around 10 percent of total energy demand in this sector. Of the 25 EJ in 2050, feedstock could account for 10 EJ, while fuel could account for around 15 EJ, or 5 percent of final energy demand.




A number of challenges need to be addressed for hydrogen to fulfil this role:

- Water is an integral component of clean hydrogen production. While hydrogen production will require far less water than other large water-consuming sectors such as agriculture, it may not be suited to production in areas with water scarcity.
- Large-scale hydrogen production and use are likely to require substantial infrastructure investment. Where current gas infrastructure exists, this may need to be repurposed for hydrogen transportation as hydrogen can cause embrittlement of some materials.
- Like methane, hydrogen is potentially hazardous and requires strict safety standards and the institutional and professional capability to enforce and maintain them. Safety issues specific to hydrogen include an almost invisible flame, and risks associated with transportation and storage of hydrogen at high pressure.
- Hydrogen transportation and storage solutions remain relatively immature. The lower energy density of hydrogen relative to natural gas requires an expansion of transportation and storage volumes or innovation in transportation and storage methods (such as storage at high pressure or storage as ammonia). While salt caverns may provide a cost-effective storage option in some geographies, this form of storage may not be sufficient in all regions.

**Low-carbon and renewable hydrogen could be close substitutes as sources of clean hydrogen supply.** Renewable hydrogen is produced from water using electrolysis powered by renewable electricity. In contrast, low-carbon hydrogen uses CCUS to capture the $CO_2$ released during production of hydrogen fuel from natural gas. Low-carbon hydrogen is typically produced from natural gas through steam methane reforming (SMR) or autothermal reforming (ATR), both mature production technologies. The GHG intensity of low-carbon hydrogen will depend on its life-cycle emissions, including upstream methane and $CO_2$ emissions, and residual emissions from the $CO_2$ capture process. Therefore, effective reduction of upstream methane emissions, use of CCUS in natural gas production, and high capture rates will be needed for low-carbon hydrogen to contribute toward achieving climate goals. In the long-term residual emissions from low-carbon hydrogen could be offset by small amounts of direct air $CO_2$ capture and storage (DACCS), potentially utilizing the same $CO_2$ transport and storage infrastructure.

31 IEA GHG (n.d.): https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/956-2018-05-the-ccs-project-at-air-products-port-arthur-hydrogen-production-facility.
32 MIT (n.d.): https://sequestration.mit.edu/tools/projects/port_arthur.html.

**The specific contribution of low-carbon hydrogen to total clean hydrogen supply is highly uncertain over the period to 2050.** Low-carbon and renewable hydrogen represent very different hydrogen production processes. The costs of low-carbon hydrogen will depend on the cost of gas, and costs of the CCUS technology. The costs of renewable hydrogen will depend on the costs of renewables and electrolyzers. In some regions, costs of renewable hydrogen are already competitive with low-carbon hydrogen. While CCUS costs are likely to fall, particularly driven by opportunities to share infrastructure as CCUS scales up, renewables and electrolyzers are expected to see very substantial cost reductions. Therefore, in the long-term, costs of renewable hydrogen are expected to fall below the costs of low-carbon hydrogen in most regions. However, there is substantial uncertainty over both the timeframe during which low-carbon and renewable hydrogen could be close substitutes and the relative contributions of low-carbon and renewable hydrogen over this period.

**Nevertheless, low-carbon hydrogen is estimated in this analysis to make an important contribution to total hydrogen supply over the period to 2050.** Figure 21 shows the composition of global hydrogen supply in the modelled scenario. Low-carbon hydrogen accounts for the majority of hydrogen production initially, but the share of renewable hydrogen rises over time and accounts for the majority of hydrogen production by 2050. The composition reflects two key determining factors. First, the cost-competitiveness of low-carbon and renewable hydrogen changes over time, with low-carbon hydrogen playing a larger role than renewable in the near term, but renewable playing the larger role in the long term. Second, renewable hydrogen scales up relatively more slowly, due to the small scale of the renewable hydrogen sector and its associated supply chain today, and constraints on the availability of renewable resources for renewable hydrogen production placed by the rapid growth in electricity production needed to meet growing electricity demand and electrification of heat and transport. Beyond these modelled factors, concerns over availability of key resources needed for renewable hydrogen production, such as water and key minerals such as platinum, could also constrain its growth rate in some regions. As a result, while it is not possible today to predict precisely how the balance between low-carbon and renewable hydrogen will evolve, it is likely that low-carbon hydrogen will account for a material share of total hydrogen supply over the period to 2050.

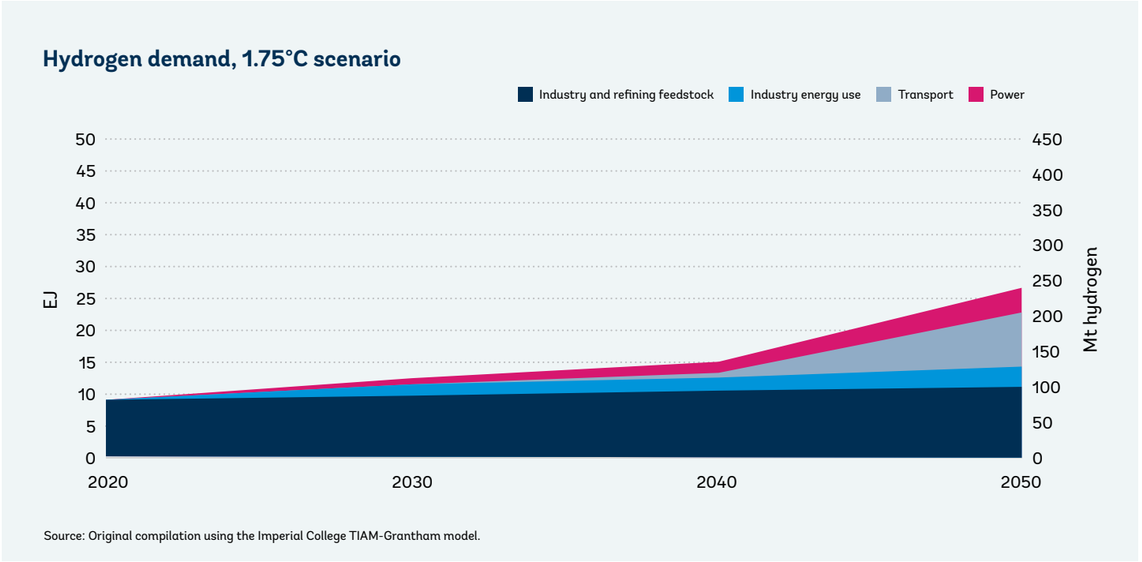
**In particular, low-carbon hydrogen offers very low-cost CCUS opportunities in ammonia and methanol production.** There are particular opportunities for low-carbon hydrogen in the production of ammonia and methanol, where hydrogen is already produced with natural gas (and, in some regions, coal). The cost of shifting from conventional hydrogen production to low-carbon hydrogen is very low, due to the high $CO_2$ content of waste gas streams produced in the steam hydrogen production process. Typically, the cost of shifting from grey to low-carbon hydrogen is around $\$25–35/tCO_2$.

**Low-carbon hydrogen is estimated to play a greater role in large gas users and gas exporters, such as the United States and the Middle East, and countries where renewable resources are relatively limited.** Low-carbon hydrogen is likely to play the greatest role in gas exporters or large gas users with very low gas prices. In regions with large renewable resources, such as the United States, the Middle East, Australia, and Mexico, low-carbon and renewable hydrogen could be close substitutes but low-carbon hydrogen is likely to remain cost-competitive for some time. Low-carbon hydrogen is also likely to play a role in gas exporters or large gas users with moderate gas prices, such as South America and developing Asia (excluding India and China). Within these regions, prospects may be strongest in countries with few renewable resources, and weaker in countries where low-cost renewable hydrogen could provide a close substitute. Finally, countries that are large producers of ammonia and methanol from natural gas, such as the United States, and India, have a particular opportunity to shift from "grey" to low-carbon hydrogen in the near-to-medium term.

**Constrained gas users are expected to either produce renewable hydrogen or source their hydrogen through imports.** Low-carbon hydrogen will face disadvantages in regions with limited accessibility and affordability of natural gas. Within these regions, prospects for low-carbon hydrogen may be weakest in countries with large renewable resources, such as China and India. Regions with few renewable resources, such as Japan and Korea, are more likely to shift to alternative technologies such as coal CCUS or bioenergy, or to source their clean hydrogen through imports. Other regions with adequate access to gas and renewable resources may nevertheless face economic incentives to import hydrogen; for example, there may be opportunities for Europe to import low-cost hydrogen from North Africa.

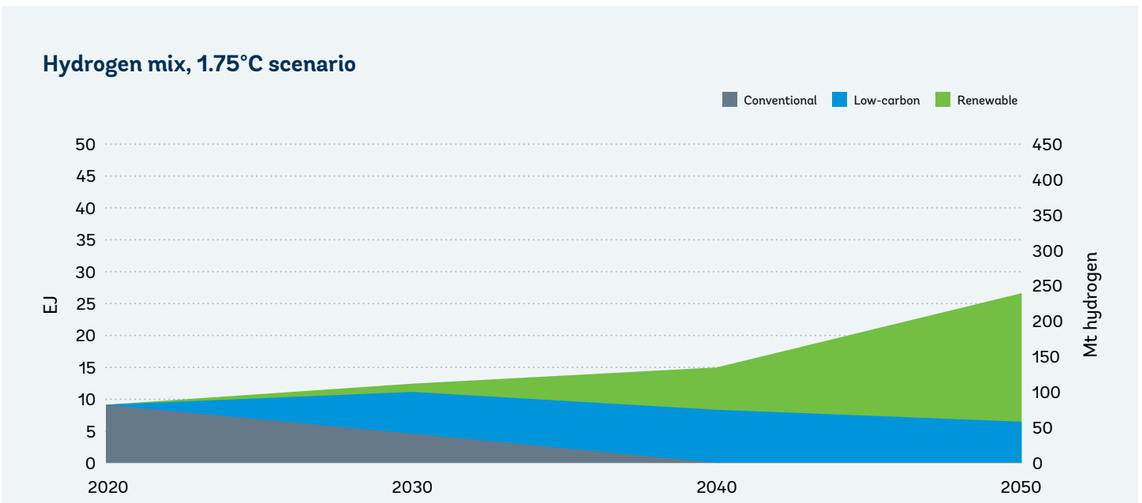


Figure 20. In a 1.75°C scenario global hydrogen demand could reach around 25 EJ (5% of final energy) by 2050



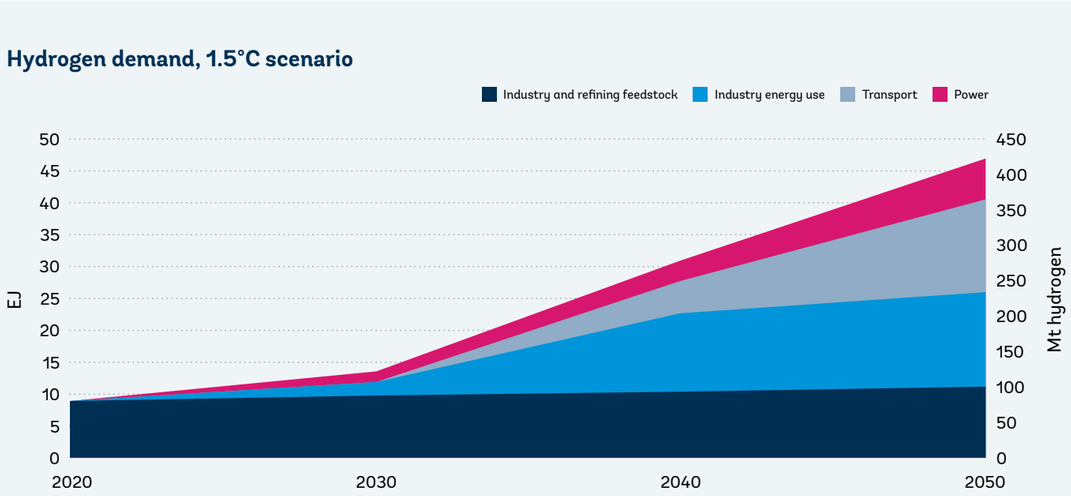

Source: Original compilation using the Imperial College TIAM-Grantham model.

Figure 21. While renewable hydrogen is likely to dominate in the long run, low-carbon hydrogen is likely to make an important contribution to supply over the period to 2050



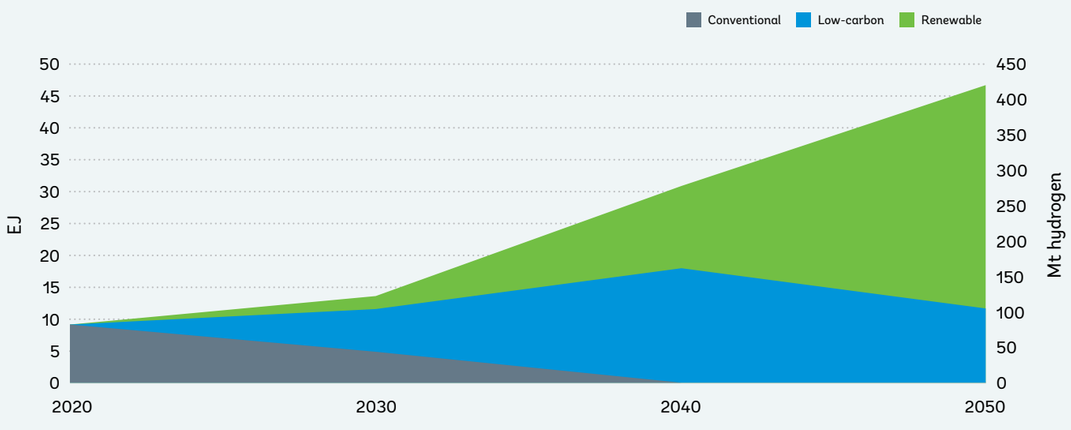

Source: Original compilation using the Imperial College TIAM-Grantham model.

Figure 22. In a 1.5°C scenario global hydrogen demand could reach 45 EJ (10% of final energy) by 2050




Source: Original compilation using the Imperial College TIAM-Grantham model.

Figure 23. A 1.5°C scenario implies a stronger role for low-carbon hydrogen




Source: Original compilation using the Imperial College TIAM-Grantham model.



**As a result, gas exporters with large gas reserves and very low domestic gas prices could emerge as low-carbon hydrogen exporters, continuing to generate revenues as use of unabated gas declines.** The difference in availability and affordability of clean hydrogen between regions could lead to valuable trading opportunities for gas exporters to export low-carbon hydrogen to constrained gas users. The energy transition poses challenges for countries that are heavily dependent on natural gas resources for economic activity, government revenues, and jobs, and exporting low-carbon hydrogen could offer an opportunity for such countries to reduce their GHG emissions while continuing to generate vital revenues and avoiding the social and economic damage of a more abrupt transition. Key exporters of low-carbon hydrogen could include Australia, Canada, and the Middle East, while key importers could include Japan, Korea, and Europe.

**In a 1.5°C scenario, hydrogen is estimated to provide up to 10 percent of final energy demand by 2050, with new demand occurring primarily in industry and implying a stronger role for low-carbon hydrogen.**

Figure 22 shows world hydrogen production in the 1.5°C scenario developed in this study. Compared to the 1.75°C scenario, hydrogen demand increases between 2030 and 2050 in the 1.5°C scenario, increasing to around 45 EJ in 2050. The increase in hydrogen demand occurs in both industry and transport, as these sectors are decarbonized more rapidly than in the 1.5°C scenario. As a result, demand for low-carbon hydrogen is likely to be more substantial in a 1.5°C scenario (Figure 23).

**Hydrogen could play a stronger role if policymakers favour this technology, or alternative technologies are slower to develop.** The future role of hydrogen in the energy system is highly uncertain, and a wide range of estimates exists for future hydrogen demand (Box 9). The wide range of possible future hydrogen demand suggests that hydrogen could play a stronger role than estimated in this study if hydrogen technologies develop more rapidly than expected, alternative technologies are slower to develop, or if consumers, businesses, and policymakers favour hydrogen over alternative climate solutions.

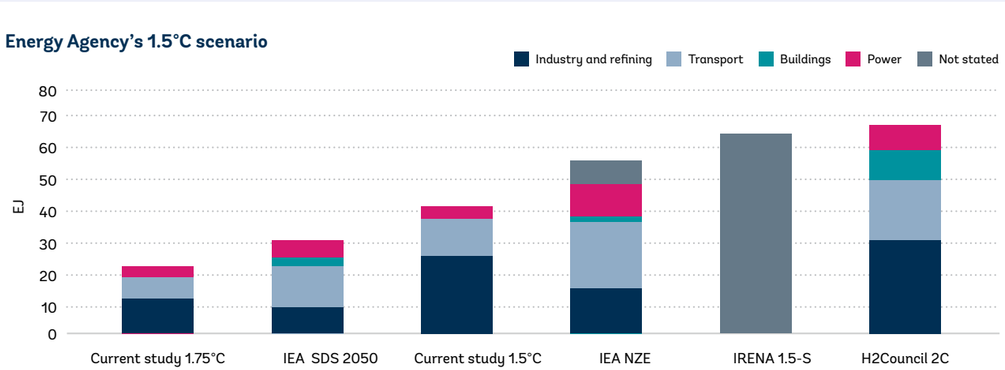


**Gas CCUS has an important role in enabling global clean hydrogen supply to meet demand over the period to 2050.** This section has set out the rationale for increasing the scale of hydrogen deployment to meet global climate objectives. Hydrogen could adopt an important role in the energy mix, satisfying around 5 percent of final primary energy demand by 2050 in a 1.75°C scenario. The scenario developed for this study is framed within a range of comparable forecasts, highlighting the uncertainty that exists surrounding future global hydrogen uptake. While acknowledging that further uncertainties surrounding the specific contributions of renewable and low-carbon hydrogen to the energy mix, this study determines a likely key role for gas CCUS in enabling global clean hydrogen supply to meet demand over the period to 2050. The likely split between renewable and low-carbon hydrogen production will vary by region and over time, as driven by relative availability of gas and renewables as well as technology costs and local circumstances. Under a 1.5°C temperature target, hydrogen demand ramps up sooner, implying a greater role for low-carbon hydrogen over the period to 2050. The following section discusses the opportunity for CCUS with gas production.

### Box 9. Scenarios for future hydrogen demand

The future role of hydrogen in the energy system is highly uncertain and will depend on the extent of international climate ambition, the relative rate of cost reductions in hydrogen technologies and alternative climate solutions, and the extent to which hydrogen and alternative climate solutions meet consumer and business needs. As a result of this uncertainty, a wide range of estimates exists for future hydrogen demand. The figure below shows hydrogen in final energy demand in the study scenarios and in selected energy scenarios.

**Hydrogen demand, present study, and selected scenarios**




The figure indicates that:

- The 1.75°C scenario developed in this study suggests that hydrogen demand could be around 25 EJ in 2050, a lower level of hydrogen demand than alternative scenarios. Relative to the study 1.75°C scenario, in IEA's Sustainable Development Scenario (SDS) hydrogen demand reaches 35 EJ in 2050, with higher demand in transport, as well as power and buildings. However, the IEA SDS is a 1.65°C scenario with lower $CO_2$ emissions in 2050. As a result of these lower $CO_2$ emissions, there is a lower need for hydrogen in the 1.75°C scenario developed for this study.
- The 1.5°C scenario developed in this study estimates a higher level of hydrogen demand than the 1.75°C scenario and the IEA SDS.
- In the 1.5°C scenario developed in this study, hydrogen demand reaches 45 EJ in 2050, or around 85 percent higher than in the 1.75°C scenario and 33 percent higher than in the IEA SDS. Relative to the IEA SDS, the 1.5°C scenario developed for this study involves substantially more hydrogen in industry and refining, offsetting slightly lower levels of hydrogen in power, buildings, and transport.
- However, there are a number of alternative scenarios with still higher levels of hydrogen demand. The IEA's Net Zero Emissions Scenario for 2050, a 1.5°C scenario, estimates around 64 EJ of hydrogen, while the IRENA 1.5-S and Hydrogen Council's Two Degrees scenarios respectively respectively estimate 74 EJ and 77 EJ in 2050.

The wide range of possible future hydrogen demand suggests that hydrogen could play a stronger role than estimated in this study if hydrogen technologies develop more rapidly than expected, alternative technologies are slower to develop, or if consumers, businesses, and policymakers favour hydrogen over alternative climate solutions.



## 2.6 Natural gas production with CCUS

### Box 10. The role of CCUS in natural gas production: Key messages

If natural gas continues to be used by countries, emissions associated with gas production and supply must be addressed, including through CCS on natural gas and LNG production. Reducing fugitive methane emissions and ending routine gas flaring is an essential part of natural gas production and use. In addition, if natural gas continues to be used, any $CO_2$ emissions associated with gas production and processing should be addressed with the application of CCUS.

CCUS with gas production and processing is a mature, cost-effective technology, supporting affordable, near-term emissions reductions. At \$15–20/t$CO_2$ CCUS on natural gas production and processing is among the cheapest applications of CCUS and among the most widely deployed, accounting for 70 percent of total CCUS deployed globally today.

The CCUS opportunity will vary by region depending on the $CO_2$ content of gas fields and the scale of LNG production. The potential to reduce emissions during upstream processing is highest in countries with high $CO_2$ content gas fields, such as Indonesia, the United States, and China; and higher still in countries with a high share of LNG in gas production.

Upstream gas processing is a significant and growing source of $CO_2$ emissions globally. This analysis estimates that CCUS with gas production and processing could capture 50–180 Mt$CO_2$ per year by 2050, depending on gas field $CO_2$ content.

**This section estimates the requirement for CCUS on natural gas production and processing globally.** It sets out the rationale for, and costs of, deploying CCUS with gas production and briefly discusses progress to date. It describes the potential role of CCUS with gas production in reducing global $CO_2$ emissions over the period to 2050, presenting a range of estimates based on gas field $CO_2$ content.

**Upstream gas processing is a significant and growing source of $CO_2$ emissions globally.** It involves separating the extracted gas mixture into methane and $CO_2$ and also removes a range of other impurities from the natural gas mixture. Global $CO_2$ emissions from natural gas production are estimated at 60–120 Mt$CO_2$ in 2020. Emissions are likely to increase over the period to 2050 as demand for natural gas increases.[33]

**CCUS with gas production can reduce the $CO_2$ emissions often vented during upstream processing of natural gas.** The $CO_2$ separated during upstream processing of natural gas is regularly vented into the atmosphere. The $CO_2$ has to be separated from the natural gas in order to meet market specifications or as part of the LNG production process, so the costs of $CO_2$ separation are already part of natural gas production economics. CCUS with gas production captures $CO_2$ emissions that would otherwise be vented, before reinjecting it for dedicated geological storage. As such, CCUS during upstream processing is the first opportunity to help decarbonize the natural gas value chain, prior to distribution or at the point of use.

**CCUS with gas production is a mature, cost-effective technology, supporting affordable, near-term emissions reductions.** As $CO_2$ separation is an inherent part of upstream gas processing, the cost of deploying CCUS with gas production is limited to transport and reinjection of captured $CO_2$. As a result, the levelized cost of $CO_2$ capture with natural gas processing is currently estimated to be lower than any other major application of CCUS, at \$15–20 per t$CO_2$.[34] Such feasibility and cost-effectiveness have accelerated deployment of upstream gas CCUS relative to other applications, with 11 facilities capturing a total of 27 Mt$CO_2$ in 2020, or around 70 percent of the total 35–40 Mt$CO_2$ captured by CCUS globally.[35, 36]

33 IEA (2020): https://www.iea.org/reports/gas-2020/2021-2025-rebound-and-beyond.
34 IEA (2021): https://www.iea.org/commentaries/is-carbon-capture-too-expensive.
35 GCCSI (2020): https://www.globalccsinstitute.com/resources/global-status-report/download/.
36 IEA (2021): https://iea.blob.core.windows.net/assets/2c510792-7de5-458c-bc5c-95c7e2560738/CarbonCaptureUtilisationandStorage_TheOpportunityinSoutheastAsia.pdf.

**CCUS with gas production allows gas exporters to reduce the life-cycle emissions of natural gas exports to global markets.** As countries and large natural gas customers seek to reduce their GHG emissions, they will increasingly source natural gas and hydrogen with lower life-cycle $CO_2$ emissions. Growing demand for lower-carbon gas and hydrogen will provide opportunities for gas exporters to offer such products to global markets. By deploying CCUS with gas production, gas exporters can reduce the emissions intensity of pipeline gas, LNG, low-carbon hydrogen, and other natural gas products.

Analysis estimates that CCUS with gas production could capture between 50 and 180 $MtCO_2$ per year by 2050, depending on gas field $CO_2$ content. As current emissions from natural gas production are highly uncertain, future abatement opportunities are also subject to a high degree of uncertainty (Box 12). To address this uncertainty, this study estimates the $CO_2$ reduction opportunity from CCUS with gas production under low, medium, and high assumptions for the $CO_2$ content of natural gas fields.

Figure 24 shows the global abatement opportunity for CCUS with gas production under each $CO_2$ assumption, over the period until 2050. In the high case, the abatement opportunity increases by 50 percent to 180 $MtCO_2$ by 2050, while in the medium case the opportunity increases 33 percent to 120 $MtCO_2$. The abatement opportunity in the low case stays largely constant over the period.

The need to reduce emissions during upstream processing is highest in countries with high $CO_2$ content gas fields, such as Indonesia, the United States, and China. Figure 25 shows global variation in gas field $CO_2$ content, for the countries studied in this report (where these values are known), and for several of the world's largest gas producers. Together, these countries are likely to account for roughly 75–80 percent of natural gas production globally, over the period to 2050.[37] Darker shading indicates higher $CO_2$ content recorded at natural gas fields and is highest in the Southeast Asia region—where recent gas production activities in Malaysia and Indonesia have recorded $CO_2$ concentrations in excess of 80 percent.[38] Gas field $CO_2$ content is similarly high in China and the United States, above average in Australia and Canada, and lower in Brazil, Kazakhstan, India, and elsewhere.

### Box 11. Capturing carbon through the Sleipner CCS project, North Sea, Norway

**The Sleipner CCS project has sequestered over 19 $MtCO_2$ produced during natural gas production since 1996.** The world's first commercial $CO_2$ injection project focused on climate change, the Sleipner CCS project off Norway's west coast, captures $CO_2$ separated from the natural gas stream produced from the Sleipner West field. Natural gas produced at the site can contain up to 9 percent $CO_2$, the majority of which is removed from the stream and would otherwise be vented into the atmosphere.[39] The project was developed following the introduction of Norway's $CO_2$ tax on offshore oil and gas emissions in 1991, beginning operations in 1996, and has since geologically sequestered over 19 $MtCO_2$.[40]



37 Study countries with known $CO_2$ concentration of natural gas fields include Brazil, China, Egypt, India, Indonesia, Kazakhstan. Auxiliary large gas producers (over 140 billion cubic meters per year) include Australia, Canada, Islamic Republic of Iran, Qatar, and the United States. Auxiliary high $CO_2$ content producers include Malaysia, Malaysia/Thailand JDA. Forecasts provided by Rystad Energy.
38 IEA (2021): https://iea.blob.core.windows.net/assets/2c510792-7de5-458c-bc5c-95c7e2560738/CarbonCaptureUtilisationandStorage_TheOpportunityinSoutheastAsia.pdf.
39 MIT (n.d.): https://sequestration.mit.edu/tools/projects/sleipner.html.
40 Equinor (n.d.): https://www.equinor.com/en/what-we-do/norwegian-continental-shelf-platforms/sleipner.html.



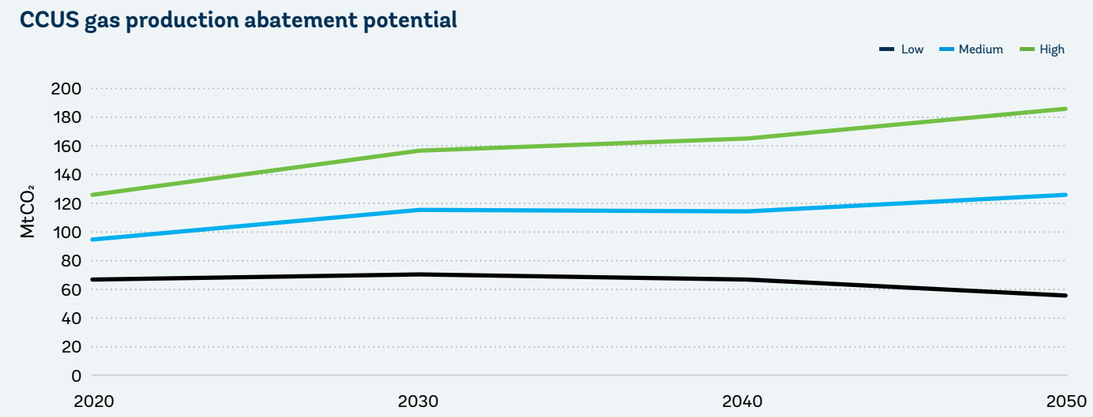
### Box 12. Gas field $CO_2$ content

Previous estimates of abatement potential of CCUS with gas production are diverse, largely due to varying assumptions regarding gas field $CO_2$ content. In 2005, the IPCC estimated the global abatement potential of CCUS with gas production at approximately 50 $MtCO_2$ per year, based on global gas field $CO_2$ content of 2–4 percent. In 2007, the IEA analysed the potential for CCUS to contribute to the Clean Development Mechanism (CDM), estimating an abatement potential of 167–334 $MtCO_2$ per year by 2020, assuming average global gas field $CO_2$ content of 7 percent. In 2008, the IEAGHG conducted a similar analysis based on a combination of known and assumed gas field $CO_2$ content values, estimating global abatement potential at 310 $MtCO_2$ per year by 2020.[41]

As data on $CO_2$ content of natural gas fields is limited, it is necessary to estimate the $CO_2$ content to assess the global opportunity. As data on $CO_2$ content are not publicly available in all cases, this study draws on proprietary data on $CO_2$ content in specific fields provided by Rystad Energy. Data is not available for all countries; therefore, in order to carry out a credible estimate of global opportunity, the study relies on data from fields in the five largest gas producing countries, and the eleven case study countries assessed in this report. As data is only available for around 25% of gasfields in these countries, country-level $CO_2$ content was estimated based on the average $CO_2$ content of fields for which data are available.

This study estimates an abatement potential range based on three assumptions of gasfield $CO_2$ content: low, medium, and high. In the high case, the weighted average gas field $CO_2$ content of the 20 countries where this is known is applied to all other gas production. In the medium case, the weighted average $CO_2$ content of the five largest gas producers globally is applied. The low case considers gas production only where $CO_2$ content is known.

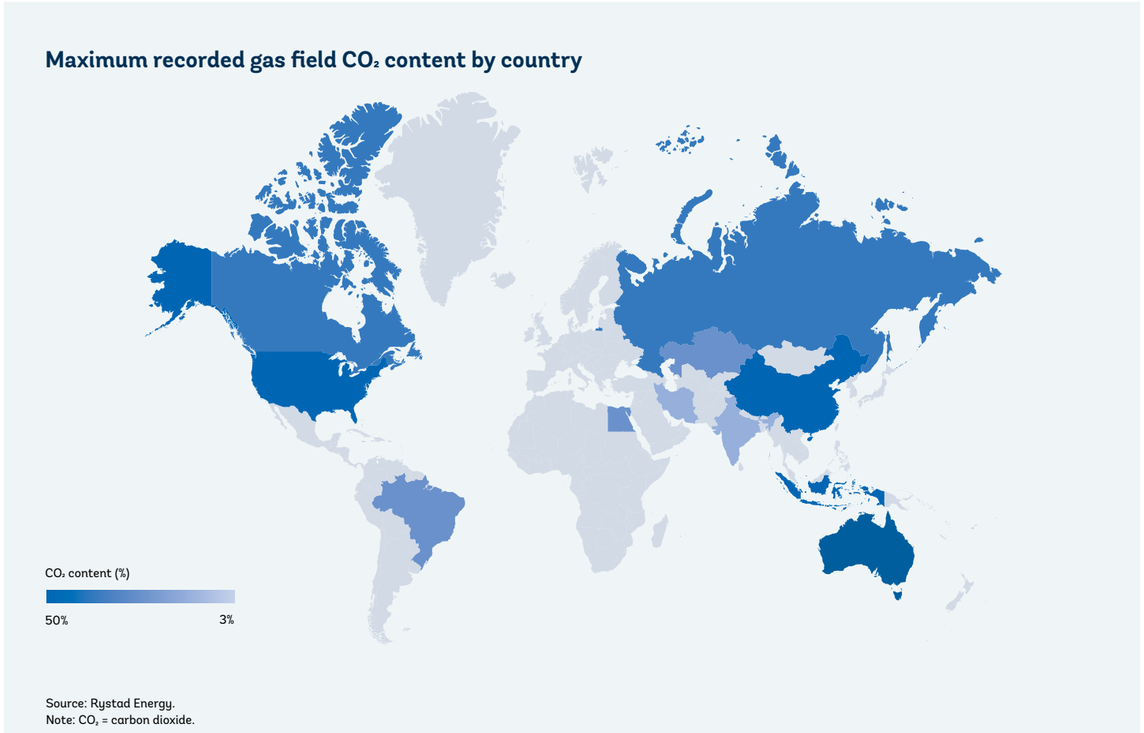
**Figure 24. CCUS with gas production could abate 180 MtCO2 globally by 2050**




Source: Original compilation.
Note: CCUS = carbon capture, utilization, and storage.

41 IEA GHG (2008): http://www.ieaghg.org/docs/General_Docs/Reports/2008-13%20CCS%20CDM%20Market%20Effects.pdf.

Figure 25. Southeast Asia, the United States, and China have high CO2 content gas fields




Source: Rystad Energy.
Note: $CO_2$ = carbon dioxide.

**The potential to reduce emissions is higher still in countries with a large share of LNG in gas production.** Liquefaction of natural gas requires the gaseous mixture to be of very low $CO_2$ content, meaning more $CO_2$ must be vented during upstream processing. As such, countries where LNG represents a large share of total natural gas production, such as Australia, Indonesia, the United Arab Emirates, and the United States, can reduce emissions further by deploying CCUS during upstream processing.

**CCUS with gas production and processing is an important technology for reducing emissions across the natural gas life cycle.** In this section, the report has set out the rationale for deploying CCUS with gas production, noting that upstream processing of natural gas is a significant and growing source of emissions. Global deployment of CCUS with gas production is advanced, due in part to separation of $CO_2$ from the natural gas mixture being an inherent part of upstream processing. Deployment of CCUS with gas production also enables gas exporters to reduce the life-cycle emissions of natural gas supplied to international markets. Upstream gas CCUS could capture up to 180 $MtCO_2$ per year by 2050, dependent largely on the $CO_2$ content of natural gas fields, although there is considerable uncertainty around the abatement potential. Countries with high $CO_2$ content gas fields face a greater need to decarbonize at the upstream processing stage, as do countries with a large share of LNG production in total gas production. The following section discusses opportunities for switching from coal and oil to natural gas with CCUS to reduce stranded asset and carbon lock-in risks.



## 2.7 Fuel-switching

### Box 13. Opportunities for fuel-switching unlocked by gas CCUS: Key messages

Viability of CCUS on natural gas use creates near-term opportunities for fuel-switching to reduce coal and oil use, provided gas combustion and industrial units are made CCUS ready when the fuel-switching occurs and CCUS is subsequently retrofitted, and upstream natural gas emissions are addressed. This analysis estimates that, in industry, fuel-switching could reduce coal and oil use by around 15 percent and $CO_2$ emissions by around 5 percent by 2030 if gas combustion and industrial units are made CCUS-ready. Emissions would then be reduced by a further 90–95 percent once CCUS is applied. In power, there is minimal scope for fuel-switching to reduce coal and oil use, given the rapid uptake of renewable energy in the sector.

Fuel-switching without the addition of CCUS is not a long-term climate solution, as continued use of unabated gas is not consistent with achieving the Paris Agreement or net zero targets. Fuel-switching is not considered a viable mitigation pathway where CCUS is not available.

This section characterizes the opportunities that gas CCUS could unlock for fuel-switching in the industry and power sectors. It sets out the rationale for switching from coal and oil to natural gas, and the conditions under which fuel-switching is an effective decarbonization strategy. It estimates the opportunity for fuel-switching in the industry and power sectors unlocked by gas CCUS in a 1.75°C scenario and explains how this opportunity is likely to vary across countries and regions. Finally, it estimates the opportunity for fuel-switching in a 1.5°C scenario and explains the differences between scenarios.

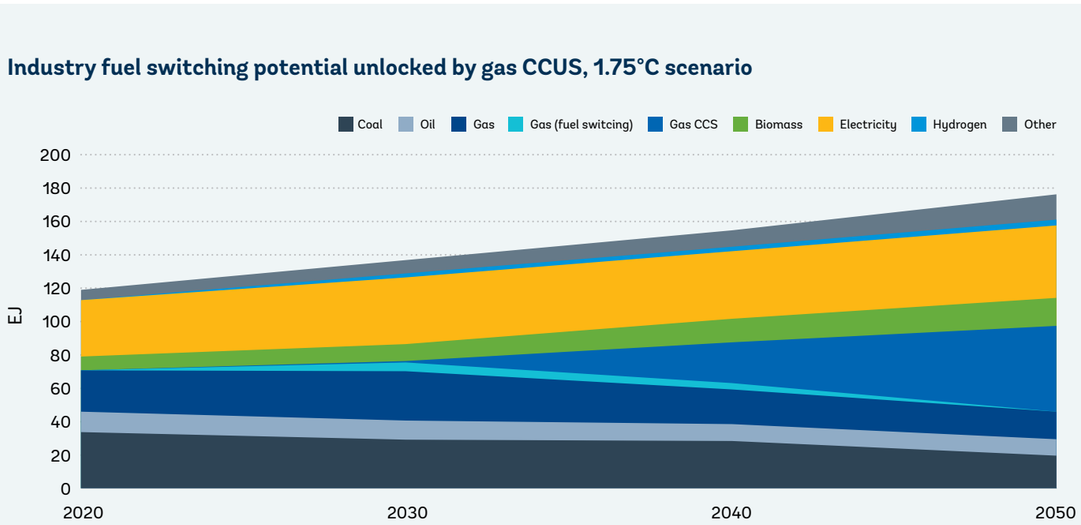
Switching from coal and oil to natural gas can offer substantial near-term emissions reductions prior to deploying gas CCUS. Combustion of natural gas releases 42 percent less $CO_2$ than combustion of coal and 24 percent less than combustion of oil. Shifting from coal and oil to natural gas in the industry and power sectors is a widely recognized option to reduce $CO_2$ emissions, provided that methane emissions from upstream and downstream natural gas are significantly reduced. While fuel-switching typically entails some costs, it does not involve the large capital investments of CCUS, and can be an affordable decarbonization solution until carbon prices rise to sufficient levels to drive CCUS deployment. In principle, the scope for switching to natural gas is substantial.

Fuel-switching without the addition of CCUS is not a long-term climate solution, as continued use of unabated gas is not consistent with achieving the Paris Agreement or net zero targets. This section focuses on the fuel-switching opportunity unlocked by CCUS application on natural gas use, rather than the overall fuel-switching opportunity.

Long-term opportunities for gas CCUS in power generation and industry could unlock opportunities for fuel switching from coal and oil to natural gas in the near to medium term. Sections 2.3 and 2.4 characterized the role of gas CCUS in the industry and power generation sectors in the 1.75°C and 1.5°C scenarios. Deployment of gas CCUS in the long term creates opportunities for fuel-switching to reduce coal and oil use in the near-to-medium term, provided gas combustion and industrial units are made CCUS-ready when the fuel-switching occurs.

In industry, fuel-switching could reduce coal and oil use by around 15 percent and emissions by around 5 percent in 2030 if gas combustion units are made CCUS ready. Figure 26 shows the industry fuel mix in a 1.75°C scenario. The contribution of gas is broken down into gas CCUS, gas-supporting switching from coal and oil, and the remaining contribution from unabated gas. Gas-supporting switching from coal and oil is defined as the volume of unabated gas that displaces coal and oil (i.e., fills the gap in supply created by the decline of coal and oil), and that subsequently shifts to gas CCUS. Over the period to 2050, coal decreases around 25 percent (with coal CCUS accounting for a substantial share of remaining coal to reduce $CO_2$ emissions), while gas CCUS eventually makes up 15 percent of total energy demand. By 2030, fuel-switching could reduce coal and oil use by around 15 percent and $CO_2$ emissions by around 5 percent, provided that gas combustion units are made CCUS-ready when the fuel-switching occurs and that CCUS is deployed in the future.

**Figure 26. In a 1.75°C scenario, fuel-switching in industry could reduce coal and oil use by around 15%**




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: Hydrogen fuel use included in "other." The figure shows energy use only; additional hydrogen used in production of ammonia and methanol is taken into account in Section 2.5: Gas CCUS for low-carbon hydrogen production. CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

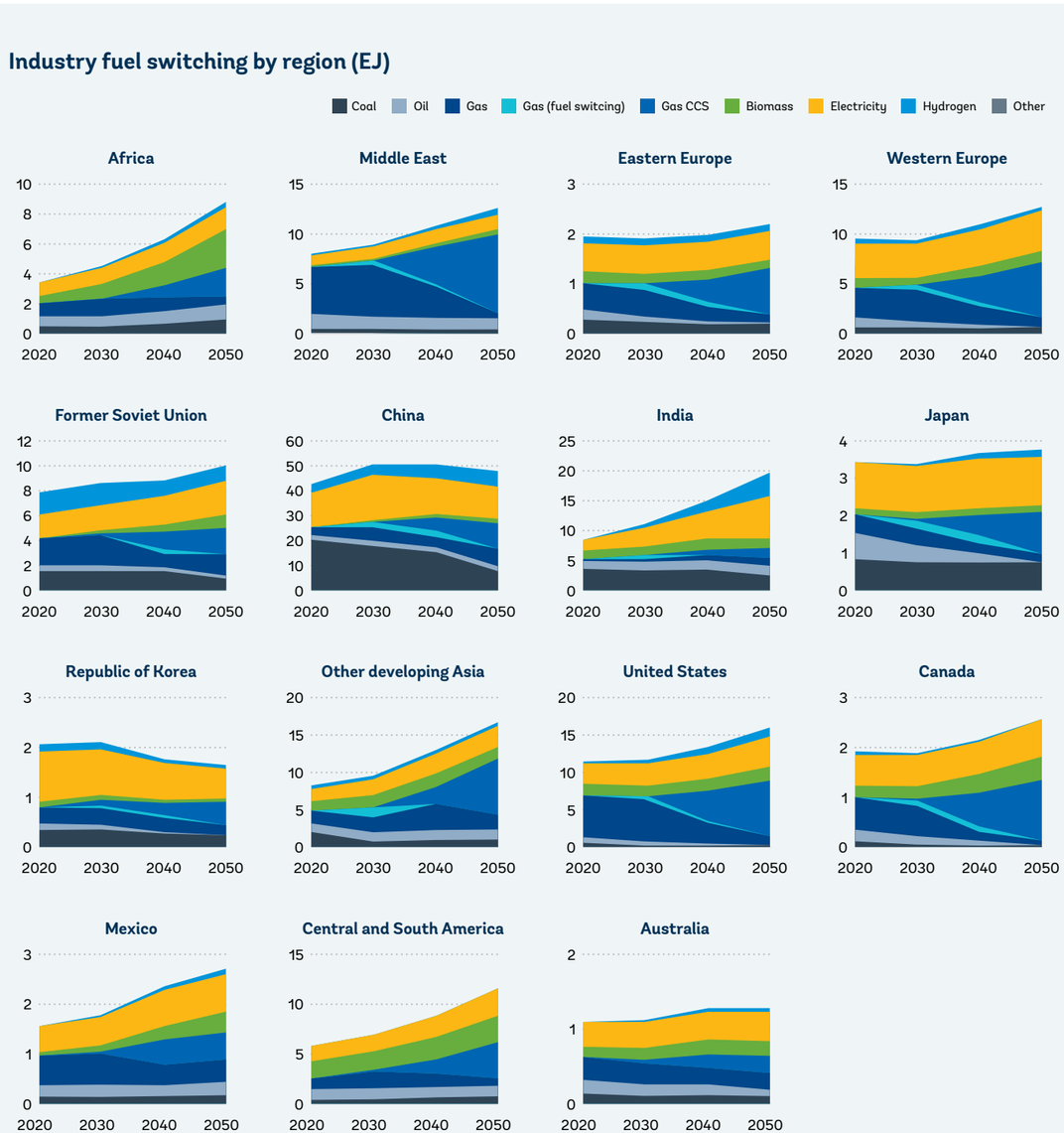
**Fuel-switching is estimated to be feasible across the majority of industry sectors.** A small number of industrial processes require specific fuels. For example, the blast furnace route to iron production requires metallurgical coal and is not suited to switching to natural gas (though gas can be used in direct reduced iron, an alternative steel production method). Further, some industrial processes use the same commodity as both fuel and feedstock, such as the use of oil in the production of plastics. However, much industrial fuel use is for the production of heat without associated feedstock, which does not require a specific fuel, and there are few fundamental barriers to shifting from coal and oil to gas.

**In a 1.75°C scenario, fuel-switching in industry is estimated to play the largest role in developing Asia, China, and the United States, potentially displacing 25–40 percent of current coal and oil use.** Figure 27 shows the fuel mix in key modelled regions in the 1.75°C scenario developed in this study. Modelling suggests that over the period to 2040, fuel-switching could reduce coal and oil use by over 40 percent in developing Asia, 35 percent in the United States, and 26 percent in China, provided that gas combustion and industrial units are made CCUS-ready when the fuel-switching occurs. Modeling also suggests that fuel-switching could reduce coal and oil use by over 15–20 percent in Australia, Canada, Eastern Europe, and the Middle East over the same period. By 2050, the fuel-switching opportunity is exhausted, as there is no further increase in unabated gas.

**Fuel-switching in industry is estimated to play a minimal role in Africa, Central and South America, the former Soviet Union, Mexico, and Korea.** Modeling suggests that, over the period to 2040, fuel-switching opportunities are likely to be limited in these countries and regions. Modeling also suggests that fuel-switching could reduce coal and oil use by 10 percent or less in Japan, Western Europe, and India. In some cases, particularly where the economics of coal are more favorable, it may be more cost-effective to shift from coal and oil to gas only in later years, when gas CCUS is available and carbon prices are high. In other cases, particularly light industry, it may be more cost-effective to shift from coal and oil to electricity.

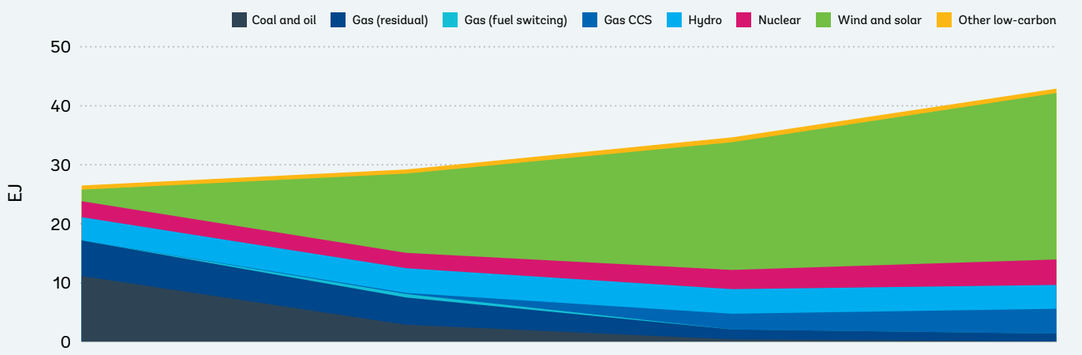


**Figure 27. Fuel switching in industry could play the strongest role in developing Asia, the United States, and China**




Source: Original compilation using the Imperial College TIAM-Grantham model.

Figure 28. In a 1.75°C scenario, power sector fuel-switching in industry could reduce coal and oil use by around 3%




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: "Other low-carbon" is predominantly wind and solar PV, though it includes small volumes of hydrogen and bioenergy with carbon capture and storage (BECCS). CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

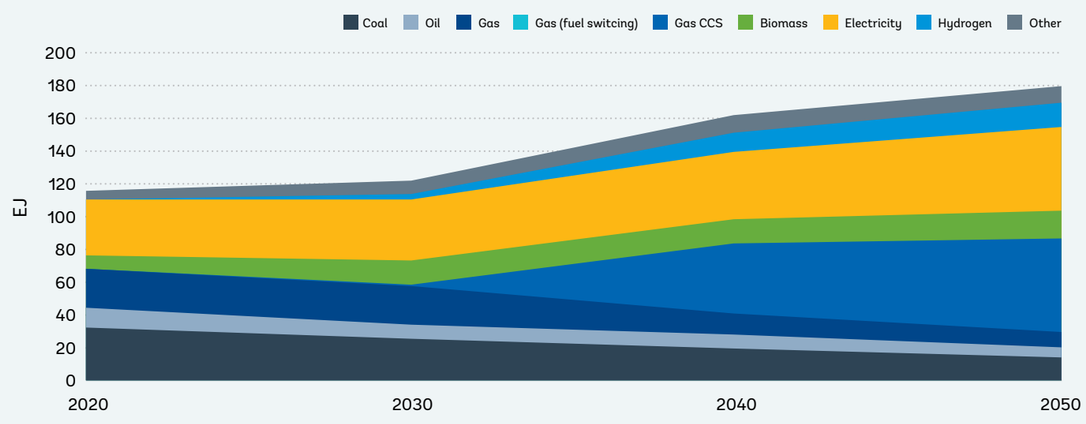
**In power, there is estimated to be minimal scope for fuel switching to reduce coal and oil use.** Figure 28 shows the power generation mix in a 1.75°C scenario. As for industry, the contribution of gas is broken down into gas CCUS, gas-supporting fuel-switching from coal and oil, and the remaining contribution from unabated gas. Over the period to 2050, coal decreases by over 55 percent, while gas CCUS eventually provides around 10 percent of generation. By 2030, fuel-switching could reduce coal and oil use by around 3 percent by 2030, provided that gas combustion units are made CCUS-ready when the fuel-switching occurs.

**In a 1.5°C scenario, there is a minimal scope for fuel-switching in both industry and power.** Figure 29 and Figure 30 show both the modelled industry fuel mix and power generation mix in a 1.5°C scenario. In industry, there is no clear role for switching from coal and oil to natural gas, as all fossil fuels are reduced from 2020 levels to achieve the climate objective. Similarly, in power, fuel-switching could reduce coal and oil use by less than 1 percent to 2040, compared with 3 percent in a 1.75°C scenario. The lower opportunity for fuel-switching is driven by the urgency of reducing all fossil generation, including gas generation, in the near term.

**Long-term opportunities for gas CCUS in the industry and power sectors could unlock opportunities for fuel switching from coal and oil to natural gas in the near to medium term.** This section has characterized the opportunities in which gas CCUS could unlock fuel switching in the industry and power sectors. Deployment of gas CCUS in the long term creates opportunities for fuel switching to reduce coal and oil use in the near-to-medium term, provided gas combustion units are made CCUS-ready when the fuel-switching occurs. In industry, fuel-switching could reduce coal and oil use by around 15 percent by 2030 if gas combustion units are made-CCUS ready and CCUS is deployed in the future. The fuel-switching opportunity will vary by region: fuel-switching could potentially displace 25–40 percent of current coal and oil use in developing Asia, China, and the United States, but is likely to play a minimal role in Africa, Central and South America, the former Soviet Union, Mexico, and Korea. In power, there is minimal scope for fuel-switching to reduce coal and oil use. In a 1.5°C scenario, there is a greater opportunity for fuel-switching to reduce coal and oil use in industry, but there remains minimal scope for fuel-switching in power. In locations where CCUS is not viable, switching to natural gas is inconsistent with long-term $CO_2$ mitigation targets. The next section discusses readiness to deploy gas CCUS at scale.

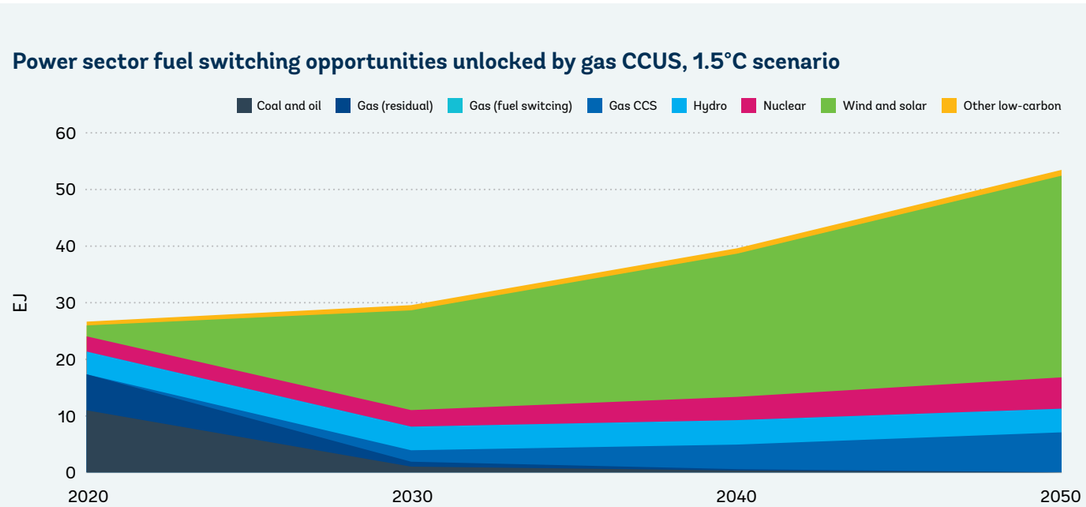


Figure 29. In a 1.5°C scenario, fuel-switching in industry could reduce coal and oil use by around 25%




Source: Original compilation using the Imperial College TIAM-Grantham model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

Figure 30. In a 1.5°C scenario, fuel-switching in the power sector could reduce coal and oil use by less than 1%




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.

## 2.8 Readiness to deploy gas CCUS at scale

### Box 14. Readiness to deploy CCUS at the global level: Key messages

Globally, readiness to deploy CCUS is variable, and particularly low in developing and emerging economies. Only a limited number of primarily countries of the Organisation for Economic Co-operation and Development (OECD) have made good progress developing a detailed assessment of domestic $CO_2$ storage sites, a comprehensive legal and regulatory framework for CCUS, and an effective policy framework to deliver CCUS projects. Further, lower- and lower-middle-income countries lag behind upper-middle- and upper-income countries in progress on these key requirements.

**This section assesses the readiness for CCUS deployment on natural gas production and use globally and in developing and emerging economies.** It assesses four aspects of readiness for CCUS: characterization of domestic $CO_2$ storage sites; a national CCUS strategy; an enabling legal and regulatory framework for CCUS; and a supportive policy framework to deliver CCUS projects. It assesses readiness at the global level, drawing on work by the Global CCS Institute (GCCSI) and others.

**CCUS deployment needs to be scaled up significantly to meet climate change targets.** Currently, 27 operating CCUS facilities have the capacity to capture more than 35 $MtCO_2$ per year. This represents a rapid increase relative to average capacity of 9–13 $MtCO_2$ over the period 1990–2010. In addition to currently operational capacity, a further 106 new CCUS facilities with capacity to capture a further 110 $MtCO_2$ per year are currently in development. However, current capacity would need to scale-up very significantly to reach the levels necessary to achieve decarbonization objectives. In the 1.75°C scenario developed in this study, gas CCUS reaches 5 $GtCO_2$ by 2050, requiring gas CCUS capacity to increase by around 165 $MtCO_2$ per year. Similarly, in the IEA's Net Zero Emissions Scenario, total CCUS reaches around 1.7 $GtCO_2$ by 2030 and 5.2 $GtCO_2$ by 2050, requiring CCUS capacity to increase by around 170 $MtCO_2$ per year. Current rates of deployment fall far short of these levels.

**A number of barriers hinder investor progress deploying CCUS at scale.** These include uncertainty over $CO_2$ storage potential, investor concern over long-term liability, and limited commercial incentives to deploy CCUS.

- **Uncertainty over adequacy of $CO_2$ storage potential at a national and local level.** Globally, $CO_2$ storage is considered to be adequate to meet the world's needs. However, at the national and local levels, uncertainty over the location, capacity, injectivity, and cost of $CO_2$ storage sites is a barrier to policymakers in effectively planning the national role of CCUS and to investors in determining the location and appraising the investment case for a CCUS project.
- **The need for legal and regulatory clarity on CCUS deployment.** CCUS involves large-scale infrastructure development, which will require laws and regulations with which CCUS developers must comply in developing CCUS projects. Lack of clarity on laws and regulations for regulatory approval, project development, and management of liabilities in many jurisdictions presents a barrier to investors and project developers financing and developing CCUS projects, as it creates challenges in appraising the investment case for a CCUS project.
- **Limited incentives to deploy CCUS in the absence of strong $CO_2$ mitigation policy.** CCUS is substantially more costly than unabated fossil technologies. The IEA estimates that even the lowest-cost applications of CCUS carry a cost of capture of \$15–25/$tCO_2$, while higher-cost applications in energy-intensive industry carry costs of \$40–120/$tCO_2$. As a result, the investment case for a CCUS project is typically weak, in the absence of strong $CO_2$ mitigation policy incentives.
- **Challenges delivering CCUS capacity.** Long development timelines are cited as barriers to large-scale CCUS deployment. Geological appraisal of storage sites can take around 3–4 years, while delivering installations could take a similar time frame.
- **Poor public awareness.** Public understanding of the need for gas CCUS to meet national climate objectives and its environmental impacts is generally poor. As a result, public perception of CCUS can be unfavorable, with key concerns cited including its sustainability, leakages and over-pressurization of the storage sites, and reduction of the public investment budget for renewable alternatives. In turn, poor public acceptance can limit the appetite for policymakers to begin a large-scale gas CCUS deployment program.



**To achieve readiness for CCUS, a number of actions are needed to overcome these barriers:**

- **Detailed storage assessment.** Clarity over the location, capacity, and cost of a country's $CO_2$ storage resource will support policymakers in effectively planning the national role of CCUS, and support investors in determining the location and appraise the investment case for a CCUS project. Further, refining the storage assessment process to account for challenges encountered in developing existing stores could give a better estimate of the scale, development cost, and developing timelines of national storage sites.
- **National CCUS strategy.** A national CCUS strategy which articulates the role of CCUS in meeting national climate objectives, sets expectations for volumes of $CO_2$ captured across sectors and over time, and explains the rationale and benefits of the role of CCUS, can reduce the barriers associated with both challenges of delivering CCUS capacity and raising public acceptance. The strategy could involve scheduling delivery of CCUS to coincide with reduced oil and gas sector activity, as oil and gas fields are decommissioned and as oil demand declines globally over the next few decades. Further, the strategy could contribute to improved public understanding and acceptance of the need for CCUS to meet national climate objectives and the low environmental risks it carries when managed effectively.
- **Development of an effective legal and regulatory framework for CCUS.** A clear and efficient legal and regulatory framework governing all aspects of a CCUS project is needed to help project developers to evaluate and deliver CCUS projects. An effective legal and regulatory framework must cover regulatory approval, the main phases of the CCUS project life cycle (construction, operation, and closure), siting and environmental and social assessment, and the allocation of liability for closure and accidental releases of $CO_2$. Further, limits on private investors' exposure to any long-term storage liabilities may be needed to unlock the business case for CCUS projects; while the risk of leakage of a well-managed storage site is considered to be minimal, a regulatory framework that does not limit liability is likely to reduce investors' appetite for financing storage projects. Options to limit private investors' exposure to long-term storage liabilities include the sharing of liabilities between the project and the state, or transfer of liabilities to the state after a specified period beyond closure of the storage site and once certain pre-agreed risk criteria are satisfied. Such liability management mechanisms would be contingent on the operator adhering to all legal and regulatory requirements and would be expected to be voided should the project proponent be found to have operated negligently. In addition to a legal and regulatory framework, clear and comprehensive technical standards governing the design and specifications of CCUS facilities and infrastructure would support efficient delivery of CCUS projects and maintain an adequate level of technical, safety, and environmental performance.
- **Development of an enabling policy framework for CCUS.** Policy incentives are typically needed to strengthen the investment case for CCUS, as is the case with other climate mitigation technologies, such as renewables. Policy incentives include carbon pricing to raise the cost of operating unabated fossil facilities; regulations and standards to limit the $CO_2$ emissions from new facilities or to require that new facilities are fitted with CCUS; financial support for the capital cost of CCUS facilities; subsidies such as feed-in tariffs to raise the revenues of CCUS facilities; or direct public investment in CCUS. Public support is also needed to address the interdependency of the CCUS value chain, for example, through public ownership of the transport and storage infrastructure in the initial phase of its operation.

**Globally, readiness to deploy CCUS is variable.** The GCCSI assesses the readiness of countries to deploy CCUS, across characterization of storage resources, suitability of the legal and regulatory framework, and development of an enabling policy framework. It categorizes countries into several bands, with Band A representing the highest level of CCUS readiness. The GCCSI's assessment indicates that only a small number of countries have characterized national $CO_2$ storage potential with the level of confidence needed to meet a net zero emissions target or possess an adequate legal and regulatory framework, while no countries have developed policies to deploy CCUS that are consistent with achieving climate goals set out in the Paris Agreement, with only a few countries providing substantial support for CCUS.

- **Few countries have developed a high degree of characterization of their storage resources.** The GCCSI assessed that in 2018, while many countries have undertaken prospective assessments of available storage capacity, only three countries (the United States, Canada, and Norway) were sufficiently storage-ready to meet national emissions reduction targets with CCUS.[42]
- **Progress adapting legal and regulatory frameworks to gas CCUS is limited globally.** The GCCSI assessed that in 2018, five countries (Australia, Canada, Denmark, the United Kingdom, and the United States) possessed an adequate legal and regulatory framework for CCUS, comprising CCUS-specific laws or existing laws that are applicable across most parts of the CCUS project cycle, and sophisticated legal and regulatory models that address the novel aspects of the CCUS process. In addition to these five countries, the EU CCS Directive establishes a legal framework for the environmentally safe geological storage of $CO_2$, covering all $CO_2$ storage in geological formations in the European Union and the entire lifetime of storage sites, as well as provisions on the capture and transport components of CCS. Further, Norway has also implemented the EU CCS Directive into law.
- **Similarly, no countries have developed CCUS strategies to guide deployment.** Of the 13 G-20 countries with net zero emissions targets, none has published a national CCUS strategy which articulates the role of CCUS in meeting national climate objectives and sets expectations for volumes of $CO_2$ captured across sectors and over time, though Natural Resources Canada states that Canada's CCUS strategy is under development.[43]
- **Only a small group of countries have developed an enabling policy framework for gas CCUS.** GCCSI assessed that, in 2018, no countries had developed policies to deploy CCUS that were consistent with achieving climate targets agreed in Paris, and only six countries (Norway, the United Kingdom, the United States, China, Canada, and Japan) fell into its band of leading countries with substantial support for CCUS, comprising both public investment in CCUS and the use of fiscal incentives and market mechanisms to encourage private sector investment. More recently, in the Netherlands specific provisions have been made for the use of CCUS within the rules of the €5 billion Sustainable Energy Transition subsidy scheme (SDE++).

**Readiness is particularly low in developing and emerging economies.** Institutional capacity to characterize storage resources, adapt legal and regulatory frameworks to gas CCUS, and develop an enabling policy framework is likely to be more limited in developing and emerging economies. The GCCSI's assessment of readiness across storage resources, a legal and regulatory framework, and enabling policy framework indicates readiness among lower- or lower-middle-income countries lags behind readiness among upper-middle- and upper-income countries:

- **Characterization of their storage resources.** The GCCSI Storage Indicator does not include any lower-middle- or lower-income countries in its highest bands, representing countries considered ready for the wide-scale deployment of storage projects (Band A), or well-advanced countries that offer the potential for wide-scale CCUS deployment (Band B). In contrast, seven of the nine countries in bands A and B are high-income, and two (China and Brazil) are upper-middle-income.
- **Legal and regulatory framework for CCUS.** The GCCSI Legal and Regulatory Indicator indicates that 30 of the 32 countries with laws that are applicable across some or most parts of the CCUS project cycle are high-income countries and two are upper-middle-income. The GCCSI's analysis suggests that no lower-middle- or lower-income countries have developed a legal and regulatory framework suitable for CCUS.
- **Enabling policy framework for CCUS.** The GCCSI Policy Indicator does not include any lower-middle- or lower-income countries in its highest bands, representing leading countries with substantial support for CCUS (Band A), or that have implemented significant policy initiatives designed to facilitate CCUS (B and B). In contrast, nine of the ten countries in bands A and B are high-income countries, and one (China) is an upper-middle-income country.

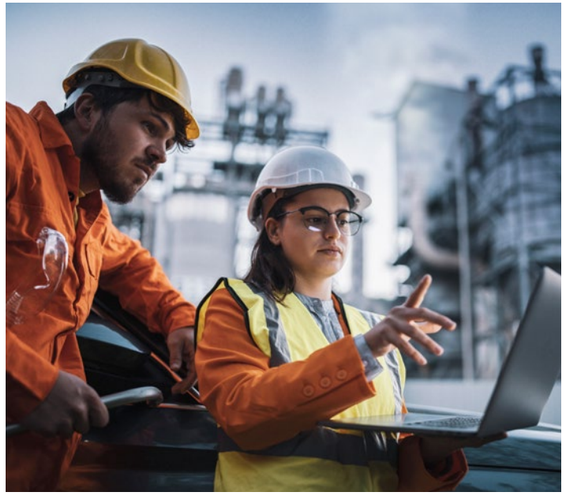
42 The GCCSI assessment of storage readiness considers the following primary criteria:
- $CO_2$ storage potential of a nation within its national borders.
- The extent of $CO_2$ storage resource development towards identifying storage capacity within suitable sites for CCS.
- The number of storage (including monitoring) operations and experience within the country.
- Proactive development of storage resources by national bodies (including academia) including working with the broader international CCS community.

43 Reviewed August 2021.



**Readiness to deploy CCUS is variable globally and particularly low in developing and emerging economies; in part as a result of this variable level of CCUS readiness, the global project pipeline is small.** This section assesses four aspects of readiness for gas CCUS: characterization of domestic $CO_2$ storage sites; a national CCUS strategy; an enabling legal and regulatory framework for CCUS; and a supportive policy framework to deliver CCUS projects. Readiness is variable across these aspects. Further, readiness is particularly low in developing and emerging economies, likely due to more limited institutional capacity in these countries. Partly due to this variable level of CCUS readiness, the global project pipeline is limited: 106 projects are currently under development, with a combined capacity to store 110 $MtCO_2$ per year, far from the scale required to deliver the 5 $GtCO_2$ of gas CCS needed to achieve a 1.75°C temperature target in the scenario developed for this study. The next chapter investigates national opportunities in gas CCUS.









# 3 National role of CCUS on natural gas production and use

## 3.1 Introduction

**This chapter assesses the prospects for CCUS on natural gas production and use in eleven developing and emerging economies.** Based on global and regional energy modelling and national trends in energy use, it characterizes national opportunities to deploy gas CCUS across four applications. Modelled national opportunities are supported by the results of a country-level assessment framework developed for this study, which aims to (1) more richly characterize the nature of the gas CCUS opportunity in a given country by assessing relative performance across key drivers of CCUS potential not reflected in the modelling, and (2) highlight key areas for development. The framework, and this chapter, considers how costs and benefits of gas CCUS could vary depending on the shares of $CO_2$ emission sources; how infrastructure requirements could vary with proximity of emissions point sources to $CO_2$ stores, and the potential enhanced oil recovery (EOR) sites. Finally, it assesses readiness for gas CCUS in each country, covering storage readiness ($CO_2$ storage resource characterization), the policy and regulatory environment, progress on gas CCUS projects to date, and national stakeholder engagement.

**This study focuses on developing and emerging economies where CCUS deployment on natural gas production and use could contribute to meeting climate targets.** Of the eleven countries considered in this study, four are large gas users, four are constrained gas users, and three are gas exporters. Key findings of national case studies and the detailed assessment framework are presented for each country in Chapter 6, "Country case studies". The countries assessed were determined through indicator-based ranking, which considered a range of technoeconomic factors to determine a short list of developing and emerging economies, likely to benefit from deploying gas CCUS to meet climate targets:

- **Large gas users**
  - Mexico
  - Egypt
  - Saudi Arabia
  - Ukraine
- **Constrained gas users**
  - Brazil
  - India
  - China
  - Vietnam
- **Gas exporters**
  - Indonesia
  - Mozambique
  - Kazakhstan

## 3.2 The application of CCUS on natural gas

**In this analysis, the estimated share of emissions covered by gas CCUS varies between countries by 2050, in a 1.75°C scenario.** Gas CCUS is estimated to mitigate over 34 percent of emissions forecast under a baseline scenario by 2050 in Mozambique, and over 20 percent in Egypt, Indonesia, Kazakhstan, Mexico, and Saudi Arabia. A more limited role is estimated in other study countries. National case study summary tables are presented in Chapter 6.

**In most countries studied, CCUS is estimated to be most required in natural gas-based industry or power generation with less deployment in gas production and low-carbon hydrogen production and use.** Table 2 shows the estimated gas CCUS abatement potential in 2050 by country and application. On average, among the 11 countries studied, industry CCUS is estimated to represents 44 percent of the gas CCUS decarbonization in 2050; power generation, 36 percent; gas production, 8 percent; and low-carbon hydrogen production and use, 12 percent, in a 1.75°C scenario. CCUS with gas power generation is estimated to play a more significant role in the former Soviet Union study countries, accounting for 82 percent of the gas CCUS decarbonization in Kazakhstan, and 50 percent in Ukraine. The application of CCUS with natural gas production is estimated to be highest in Indonesia (29 $MtCO_2$ in 2050), though it is most significant in Mozambique, where it represents 75 percent of the country's total abatement opportunity.

**Table 2. National gas CCUS abatement opportunities are largest in industry by 2050 (MtCO2/year)**

| Country | Industry | Power | Gas production | Low-carbon hydrogen | Total |
|---|---|---|---|---|---|
| **Brazil** | 79 | 9 | 1 | 2 | **90** |
| **China** | 586 | 279 | 10 | 122 | **997** |
| **Egypt, Arab Rep.** | 30 | 27 | <1 | 5 | **63** |
| **India** | 91 | 16 | <1 | 52 | **159** |
| **Indonesia** | 124 | 38 | 29 | 35 | **226** |
| **Kazakhstan** | 5 | 39 | <1 | 3 | **47** |
| **Mexico** | 33 | 48 | <1 | 4 | **86** |
| **Mozambique** | <1 | 1 | 5 | 1 | **6** |
| **Saudi Arabia** | 105 | 63 | 5 | 7 | **180** |
| **Ukraine** | 9 | 11 | <1 | 1 | **22** |
| **Vietnam** | 17 | 21 | <1 | 2 | **40** |

Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: The approach to estimating the national opportunity is described in the technical annex to this report. CCUS = carbon capture, utilization, and storage.

**Accessibility and affordability of natural gas and country size jointly determine the need for CCUS on natural gas production and use.** Applications of CCUS on natural gas production and use are substantial for countries that are both large in size, and have accessible and affordable natural gas. For example, the gas CCUS opportunities in Indonesia are estimated to be among the five largest of the eleven case study countries. In some cases, applications are substantial for very large countries even without accessible and affordable natural gas. For example, China has the largest gas CCUS application among the eleven case study countries, driven by its large population and the scale of the energy system needed to meet energy demand. Similarly, the application in India is among the fifth largest of the eleven case study countries, despite severe constraints on accessibility and affordability of natural gas. At the other end of the scale, applications for gas CCUS are most limited in absolute terms for countries that are small in size, even with accessible and affordable natural gas. For example, Kazakhstan, Ukraine, and Mozambique are in the bottom five of the eleven case study countries, due to their relatively smaller populations of under 100 million inhabitants, despite being either large gas users or gas exporters and having a high level of accessibility and affordability.

**The cost of deploying gas CCUS varies based on the source of captured $CO_2$.** Table 3 shows the estimated levelized cost of $CO_2$ capture by application and initial $CO_2$ concentration. The cost of deploying CCUS is highest for cement and iron and steel production, where the $CO_2$ content of flue gas streams is relatively low. Costs are lower for low-carbon hydrogen production, and lower still for the associated production of ammonia and methanol, where the $CO_2$ content of flue gas streams is higher. Capture costs are lowest for CCUS with natural gas production, where the $CO_2$ content of flue gas streams is near pure.



**Table 3. The levelized cost of $CO_2$ capture is highest in heavy industry, 2019 ($/t$CO_2$)**

| $CO_2$ source | Lower bound | Upper bound |
|---|---|---|
| **Industry (iron and steel, cement)** | 40 | 120 |
| **Hydrogen (steam methane reforming)** | 50 | 80 |
| **Power generation** | 40 | 80 |
| **Ammonia and methanol production** | 25 | 35 |
| **Natural gas processing** | 15 | 25 |

Source: lhttps://www.iea.org/commentaries/is-carbon-capture-too-expensive.

**Low-cost gas CCUS applications in natural gas processing and ammonia and methanol production are expected to be present in most countries.** Across the countries considered in this report, low-cost ($15–35/t$CO_2$) gas CCUS applications in natural gas processing and ammonia and methanol production average 15 Mt$CO_2$/year by 2030 and 33 Mt$CO_2$/year by 2050. Such applications are particularly significant, as their low costs can help facilitate the near-term deployment of CCUS in these countries. While low-cost opportunities dominate the near-term CCUS potential in most study countries, they are estimated to remain particularly high over the period to 2050 in India and Mozambique, representing 33 percent and 75 percent of the total yearly gas CCUS abatement opportunity in each country respectively, by mid-century. In India, this is due primarily to low-carbon hydrogen being expected to largely replace natural gas as a feedstock in the production of significant quantities of ammonia and methanol over the period to 2050. In Mozambique, natural gas production is expected to increase significantly over the same period, while opportunities in industry and power generation are more limited.

**The infrastructure requirements of $CO_2$ storage will vary based on the proximity of emission sources to gas pipelines and potential storage sites.** The need for extensive infrastructure will depend on the distance of emission point sources to potential storage sites. As an illustrative example, Figure 31 maps power generation emissions relative to potential storage sites in Ukraine and Mexico. In Ukraine, 66 percent of power emissions are generated within 100 km of potential storage sites, implying low $CO_2$ transportation infrastructure requirements to store captured $CO_2$. Conversely, in Mexico, 42 percent of power emissions are generated within 100 km of potential storage sites, implying moderate $CO_2$ transportation infrastructure requirements. Similar source-sink mapping is summarized for each country in the case study summary tables in Chapter 6.

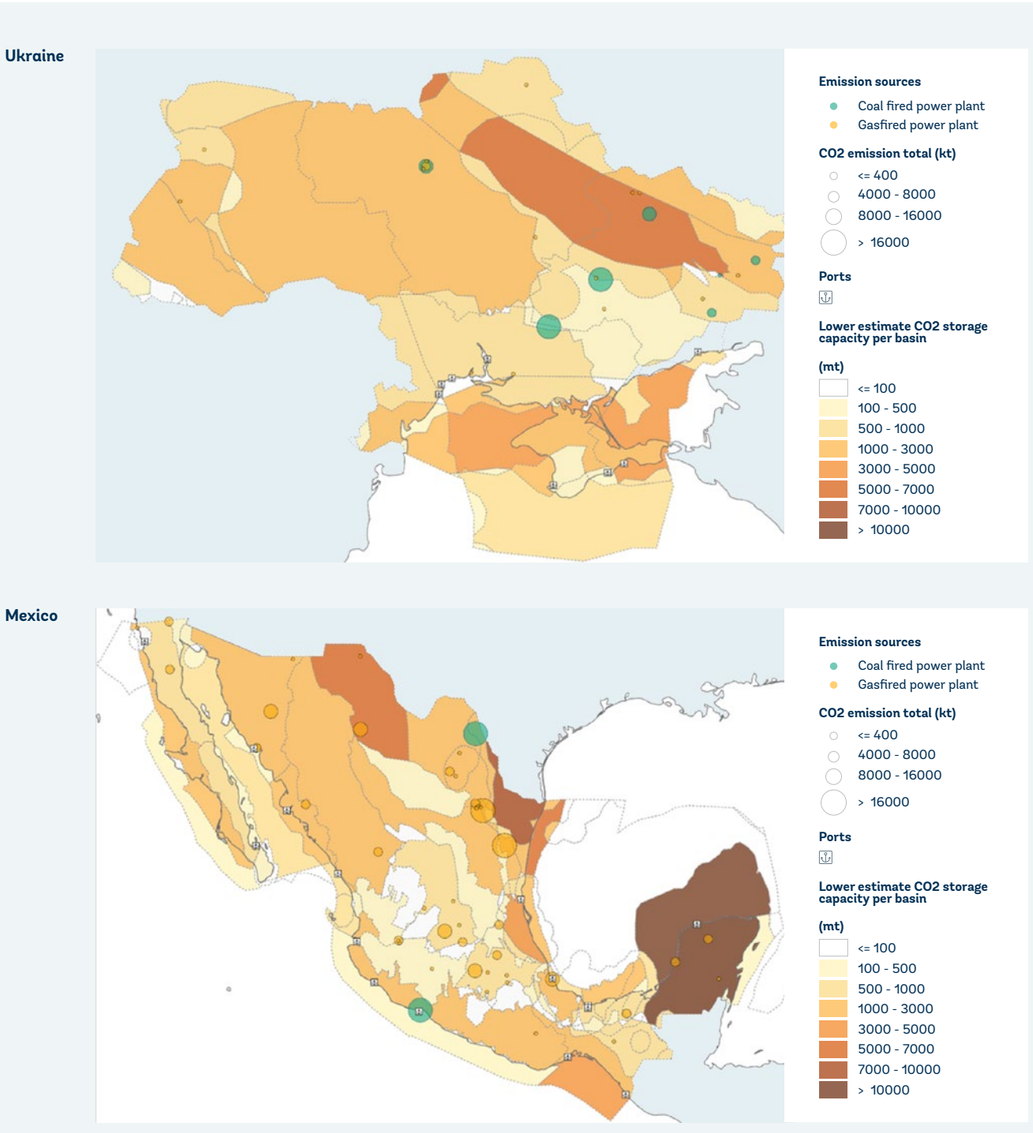
## 3.3 Country variation in readiness to deploy CCUS

**All eleven study countries demonstrate low levels of readiness to deploy gas CCUS across four key dimensions.** This section analyses the countries' performance on these four determinants: state of $CO_2$ storage characterization, national CCUS-relevant legal and regulatory environment, national CCUS-relevant policy environment, and key stakeholder engagement.

**Most study countries now have climate commitments that require deployment of CCUS.** In Egypt and Mexico, climate targets require emissions to be reduced by less than 40 percent compared to the business-as-usual scenario—which is insufficient for the deep decarbonization of the power sector and energy-intensive industry through CCUS. Meanwhile, Mozambique targets a greater than 40 percent reduction in emissions, but lacks a long-term emissions reduction goal. However, the majority of the study countries—Kazakhstan, , Ukraine, Brazil, China, India, Indonesia, Saudi Arabia, and Vietnam—have all stated long-term net zero emissions targets, many of which were announced at the COP26 international climate summit in late 2021.

**All these countries have undertaken high-level assessments of the potential for $CO_2$ storage but need to develop more detailed characterizations of domestic storage sites to deploy CCUS at scale.** Preliminary estimates suggest that adequate storage volumes exist in all eleven countries to sequester domestic emissions throughout their transition to net zero. In Egypt, India, Kazakhstan, Mexico, Mozambique, Ukraine, and Vietnam, though high-level characterizations suggest adequate storage volumes, the exact location and capacity of these sites remains highly uncertain. In Brazil, China, Indonesia, and Saudi Arabia, however, similar high-level estimates are complemented by site-specific wellhead data, improving confidence in the storage characterization at these sites. The study countries need to

**Figure 31. The location of power emissions relative to potential storage sites implies only modest infrastructure needs in Mexico, but more extensive ones in Ukraine**




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage.



carry out further site-specific testing to instil confidence among policymakers that their storage volumes are favourable to CCUS deployment at scale.

**The existing legal and regulatory frameworks are not conducive to efficient delivery of CCUS projects.** CCUS-specific regulation is largely absent from the legal frameworks of the study countries. No CCUS regulatory framework exists in Egypt, India, Kazakhstan, Mozambique, Ukraine, and Vietnam, so project developers there lack clarity and support in evaluating and delivering CCUS projects. Meanwhile, in Brazil, China, Indonesia, and Saudi Arabia the existing CCUS projects are typically governed by oil and gas industry regulations or developed by state-owned enterprises. While this is sufficient to support the few pilot and commercial CCUS projects in these countries, delivery of CCUS at scale requires greater certainty surrounding all stages of the project life cycle. In particular, legal frameworks in these regions lack clarity on the long-term liability for stored $CO_2$.

**Private and public CCUS financing mechanisms are lacking among our eleven study countries, with carbon prices low or non-existent and public funding limited.** Creating a policy environment that raises the cost of unabated fossil fuel use can incentivize CCUS deployment. Carbon pricing mechanisms to achieve this are implemented or under development in eight of the eleven study countries; however, current prices are typically too low to incentivize investment in CCUS. Public funding for CCUS development is also absent in Egypt, Kazakhstan, Mexico, Mozambique, Ukraine, and Vietnam, though Brazil, China, Indonesia, India, and Saudi Arabia have dedicated more substantial resources to CCUS research and development.

**Engagement between industry, national government, and international actors is insufficient to deliver CCUS at scale in most study countries.** Delivering CCUS at the scale necessary to achieve global and national emissions reduction targets requires the joint efforts of project developers, national governments, and international development organizations. In the majority of our study countries, industry stakeholders and governments are not collectively aligned toward CCUS as a solution to deliver climate targets, with relevant public authorities, potential project developers, and academic and research institutions lacking consensus over the necessity to deploy CCUS, and how, where, and when such projects would be implemented. Some progress has been made in Brazil, China, Indonesia, India, and Saudi Arabia, where greater public investment and more operational projects are evidence of a greater alignment between developers and national governments. In India, the Department for Science and Technology has committed over €1 million to support Indian applications for Accelerating CCUS Technologies grants (ACT), while industry stakeholders such as Tata Steel and Dalmia Bharat are developing demonstrative $CO_2$ capture and utilization (CCU) facilities.







# 4 Regional cooperation on CCUS on gas

### Box 15. Cross-border cooperation in gas CCUS: Key messages

- **Regional cooperation on gas CCUS could be advantageous in meeting climate targets for both exporters and importers of $CO_2$.** For $CO_2$ exporters, CCUS with domestic $CO_2$ storage resources alone may be technically infeasible, so outsourcing storage facilities may be an alternative decarbonization option. For $CO_2$ importers, offering regional $CO_2$ storage services could generate revenues, lowering the cost of meeting national climate targets.
- **In all regions assessed, there is adequate $CO_2$ storage potential in prospective importing nations to fully meet the region's storage needs.**
- **Among the regions analyzed in this report, cooperation on CCUS is likely to be of greatest value in Southeast Asia,** where $CO_2$ exporters account for around 27 percent of total regional emissions, while in Central Asia and the Middle East and North Africa (MENA) region, $CO_2$ exporters account for roughly 3 percent and 1 percent of total regional emissions, respectively.

This chapter estimates applications for regional cooperation in cross-border $CO_2$ trade with gas CCUS. First, it sets out the rationale for establishing regional $CO_2$ trade, highlighting how both importers and exporters of captured $CO_2$ stand to benefit. Second, it discusses how storage resources and technical capacity are the key determinants of $CO_2$ trade balance, before summarizing insights from three world regions: Central Asia, MENA, and Southeast Asia. Third, it presents case study summaries, detailing import-export patterns between constituent countries and overall regional adequacy for cooperation on $CO_2$ storage.

Cross-border cooperation could enable countries with limited technical capacity or $CO_2$ storage potential to deploy CCUS to meet climate targets. In countries with limited oil and gas infrastructure and technical expertise, deploying CCUS to meet climate targets may be prohibitively difficult or expensive. For such countries, exporting captured $CO_2$ to neighbouring countries with the technical capacity to reinject $CO_2$ can facilitate domestic deployment of CCUS. Further, deploying CCUS could be infeasible in countries with limited $CO_2$ storage resources. Exporting captured $CO_2$ to neighboring countries with greater capacity solves this issue, enabling the deployment of CCUS to meet climate targets, even where storage resources are low.

Cross-border cooperation could enable $CO_2$ importers to generate revenues by offering storage services to neighboring countries. For countries with established infrastructure and expertise surrounding transport and reinjection of captured $CO_2$, and sufficient storage resources, cross-border $CO_2$ trade presents a revenue-generation opportunity. As such, by offering $CO_2$ storage services to neighbors, a country can lower the cost of meeting its own climate targets, while facilitating the deployment of CCUS.

### Box 16. Northern Lights CCS project, North Sea, Norway

Norway's cross-border Northern Lights CCS project will offer 1.5 $MtCO_2$/year in offshore storage services to emitters across Europe by 2024. As the transport and storage component of Norway's Longship CCS project, the Northern Lights terminal can receive shipments of liquefied $CO_2$ from across Europe and sequester it beneath the North Sea. The project will be the world's first open-source, cross-border carbon storage infrastructure network. Originally intended to be built to 5 $MtCO_2$/year capacity, developers announced in September 2021 that this target would be stepped up in response to increased interest in the project from industrial customers across Europe.[44] Equinor, the project's chief licensee, estimates capital costs at approximately $700 million, partly supported by the Norwegian government.[45]

44 Northern Lights CCS (2021). https://northernlightsccs.com/news/northern-lights-announces-growth-ambitions/.
45 Offshore Energy (2021). https://www.offshore-energy.biz/norway-approves-plan-for-northern-lights-project/.

**This study analyses opportunities for cross-border cooperation in gas CCUS in three regions,** while considering two key drivers of $CO_2$ trade balance: technical capacity to deliver CCUS and adequacy of domestic $CO_2$ storage resources. In this analysis, a country is defined as a $CO_2$ importer if:

- It has a mature oil and gas industry, indicating it has the technical capabilities to carry out the range of activities needed to deliver CCUS. The oil and gas industry is considered mature if domestic oil and gas production amount to at least 20 percent of total primary energy supply.
- It has adequate storage capacity for domestic $CO_2$ emissions. Storage capacity is considered adequate for import if it can store at least 50 years of current territorial $CO_2$ emissions.

The three study regions are:

- Central Asia (Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, Uzbekistan).
- The Middle East and North Africa (Algeria, Egypt, the Islamic Republic of Iran, Iraq, Jordan, Oman, Qatar, Saudi Arabia, the United Arab Emirates).
- Southeast Asia (Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, Vietnam).

**$CO_2$ trade is likely to be mutually advantageous for countries in Central Asia and Southeast Asia, but less so in the MENA region, which is dominated by $CO_2$ importers.** In Central Asia, Kazakhstan, Turkmenistan, and Uzbekistan have sufficient technical capacity and storage resources to become $CO_2$ importers, while the Kyrgyz Republic and Tajikistan are likely to export captured $CO_2$. This implies that all countries within the region stand to benefit from cross-border cooperation on gas CCUS, either through facilitation of CCUS deployment or through revenue generation. A similar pattern emerges in Southeast Asia, where Brunei Darussalam, Indonesia, Malaysia, Myanmar, Timor-Leste, and Vietnam are likely to import $CO_2$ from Cambodia, the Lao PDR, the Philippines, Singapore, and Thailand. In the MENA region, only Jordan is likely to export $CO_2$; however, a number of countries adjacent to the MENA region, including Turkey and India, have large $CO_2$ emissions and potentially limited technical capacity for domestic CCUS due to the absence of a large oil and gas industry.

**In all regions assessed, there is adequate $CO_2$ storage potential in prospective importing nations to fully meet the region's storage needs.** Regional adequacy for cross-border $CO_2$ trade is dependent on the cumulative storage capacity of importers within the region and the total $CO_2$ emissions of the region. Regional adequacy is highest in Central Asia, where current regional emissions could be stored for over 1,500 years. In the MENA region and Southeast Asia, importers' storage potential is relatively lower, but highly adequate overall, with capacities of around 450 and 220 years, respectively.

**Among the regions analysed in this report, cooperation on CCUS is likely to be of greatest value in Southeast Asia, where emissions arising from identified $CO_2$ exporters represent roughly 27 percent of total regional emissions.** This suggests a significant role for regional cooperation on CCUS in achieving climate targets in the region. The value of cross-border cooperation on CCUS is more limited in Central Asia and the MENA region, where $CO_2$ exports represent roughly 3 percent and 1 percent of total regional emissions respectively.

**Development of detailed regional CCUS roadmaps could catalyse regional cooperation on gas CCUS.** This section has identified a number of opportunities for regional cooperation on gas CCUS. These opportunities suggest that regional cooperation could be an important element of deploying gas CCUS in many countries. Development of CCUS roadmaps could provide detailed evidence supporting regional cooperation and set out the actions needed for policymakers and businesses to benefit from this cooperation and accelerate deployment of CCUS. Effective roadmaps would assess the likely decarbonization pathways of different countries within each region, and likely volumes of $CO_2$ captured in each country; identify countries with comparative advantages in storage capacity and technical capability to store $CO_2$; and identify actions for policymakers and businesses to develop the international cooperation necessary to deliver a successful regional $CO_2$ storage industry.



## 4.1 Regional case studies

This report identifies likely patterns of cross-border cooperation on CCUS based on $CO_2$ storage potential and technical capacity in Central Asia, the MENA region, and Southeast Asia. It considers national storage capacity and oil and gas production as a percentage of total primary energy supply as the indicator of a country's $CO_2$ trade balance. The total storage capacity of $CO_2$ importers in each region exceeds total regional emissions, suggesting that regional cooperation on CCUS could be advantageous in all areas studied. Regional storage adequacy is reported and measured as the number of years for which current regional emissions could be sequestered, given total regional storage volumes.



Table 4. Case study summary: Central Asia

| | Country | Domestic storage capacity ($GtCO_2$) | Domestic emissions ($MtCO_2$) | Domestic storage adequacy (years) | Oil and gas production (% of primary energy supply) |
|---|---|---|---|---|---|
| Importers | Kazakhstan | 253 | 143 | 1,766 | 160 |
| | Turkmenistan | 98 | 28 | 3,471 | 290 |
| | Uzbekistan | 30 | 69 | 436 | 90 |
| Exporters | Kyrgyz Rep. | 4 | 3 | 1,331 | 6 |
| | Tajikistan | 8 | 4 | 1,979 | 2 |
| Importer storage capacity ($GtCO_2$) | | | 381 | | |
| Regional emissions ($MtCO_2$) | | | 248 | | |
| Regional storage adequacy (years) | | | 1,541 | | |
| Value of cross-border storage (exporter emissions as % of regional emissions) | | | 3 | | |

Source: Original compilation.

Table 5. Case study summary: Middle East and North Africa

| | Country | Domestic storage capacity ($GtCO_2$) | Domestic emissions ($MtCO_2$) | Domestic storage adequacy (years) | Oil and gas production (% of primary energy supply) |
|---|---|---|---|---|---|
| Importers | Algeria | 141 | 64 | 2,204 | 205 |
| | Egypt, Arab Rep. | 71 | 152 | 470 | 63 |
| | Iran, Islamic Rep. | 61 | 303 | 200 | 155 |
| | Iraq | 84 | 94 | 893 | 619 |
| | Oman | 22 | 38 | 578 | 378 |
| | Qatar | 8 | 74 | 109 | 720 |
| | Saudi Arabia | 140 | 354 | 395 | 362 |
| | United Arab Emirates | 26 | 142 | 179 | 555 |
| Exporters | Jordan | 7 | 11 | 649 | 19 |
| Importer capacity ($GtCO_2$) | | 553 | | | |
| Regional emissions ($MtCO_2$) | | 1,232 | | | |
| Regional storage adequacy (years) | | 449 | | | |
| Value of cross-border storage (exporter emissions as % of regional emissions) | | 1 | | | |

Source: Original compilation.



Table 6. Case study summary: Southeast Asia

| | Country | Domestic storage capacity ($GtCO_2$) | Domestic emissions ($MtCO_2$) | Domestic storage adequacy (years) | Oil and gas production (% of primary energy supply) |
|---|---|---|---|---|---|
| Importers | Brunei Darussalam | 3 | 5 | 525 | 422 |
| | Indonesia | 128 | 405 | 315 | 30 |
| | Malaysia | 42 | 167 | 254 | 78 |
| | Myanmar | 54 | 21 | 2,489 | 79 |
| | Vietnam | 20 | 227 | 86 | 23 |
| | Timor-Leste | 6 | <1 | 28,500 | 221 |
| Exporters | Cambodia | 3 | 6 | 430 | 0 |
| | Lao PDR | 1 | 15 | 91 | 0 |
| | Philippines | 4 | 87 | 49 | 1 |
| | Singapore | 0 | 40 | 0 | 4 |
| | Thailand | 25 | 162 | 153 | 15 |
| Importer capacity ($GtCO_2$) | | 252 | | | |
| Regional emissions ($MtCO_2$) | | 1,135 | | | |
| Regional storage adequacy (years) | | 222 | | | |
| Value of cross-border storage (exporter emissions as % of regional emissions) | | 27 | | | |

Source: Original compilation.





# 5 Roadmap to deploy CCUS on natural gas at scale

### Box 17. Roadmap to CCUS deployment: Key messages

- **If countries continue to produce and use natural gas, policymakers will need to accelerate the assessment and deployment of CCUS, if they are to achieve the Paris Agreement and national and global net zero emissions goals.** Action is needed across three key phases of CCUS deployment: planning, scale-up, and rollout.
- **The planning phase involves preparatory activities to deliver CCUS in the later phases.** In this phase, policymakers should first work toward a strategic decision on the role of gas CCUS, before achieving readiness for accelerated CCUS deployment.
- **The scale-up phase involves developing early commercial-scale CCUS projects and building out the transport and storage infrastructure.** In this phase, policymakers should provide financial support for initial CCUS projects, and develop effective CCUS funding mechanisms supported by economic policy reforms where necessary.
- **The rollout phase involves wider deployment of CCUS to achieve emissions reduction targets.** In this phase, policymakers should continue to assess the business case for CCUS to inform future investment decisions; support sustained CCUS deployment; and ensure the funding mechanism continues to deliver value for money.
- **CCUS on natural gas is likely to be relevant in developing and emerging economies, in particular large gas users and gas exporters, so international financial institutions such as the World Bank, Asian Development Bank, and Green Climate Fund have a crucial role to play in supporting them to deliver CCUS in order to achieve the Paris Agreement goals.** International financial institutions have a role in providing technical assistance relating to CCUS; in providing grants supporting country strategies and roadmaps for CCUS uptake; in supporting the development of policies, regulations, and standards; in building capacity to design and operate CCUS projects; in supporting CCUS pilot projects in industry and across the economy; in identifying opportunities to benefit local communities, create jobs, and meet climate, environmental, and social objectives; and in mobilizing climate finance and providing access to guarantees to deliver CCUS investment that is sustainable.
- **Should CCUS not be available or deployed by countries that continue to produce and use natural gas, Paris Agreement targets will become signficantly more challenging and more expensive to meet, with a high likelihood that targets will be exceeded.**

**If countries continue to produce and use natural gas, policymakers will need to accelerate the assessment and deployment of CCUS to meet their Paris commitments. This chapter identifies actions for policymakers, supported by international financial institutions such as the World Bank, to accelerate deployment of CCUS and support achievement of emission goals.** It identifies the policy actions needed at three stages of CCUS deployment: the planning, scale-up, and rollout phases. It draws out specific recommendations for policymakers in three key country groups: large CCUS users, gas exporters, and constrained CCUS users. Finally, it identifies actions for international financial institutions to support policymakers in developing and emerging economies to accelerate deployment of gas CCUS.

**A strong climate commitment is a prerequisite to CCUS.** A strong climate commitment (such as ambitious NDC goals, a net zero emissions target, or other deep decarbonization targets) is necessary to underpin policy efforts to reduce GHG emissions including through CCUS, and to signal to businesses and investors that CCUS is likely to play an important role in the future energy system.

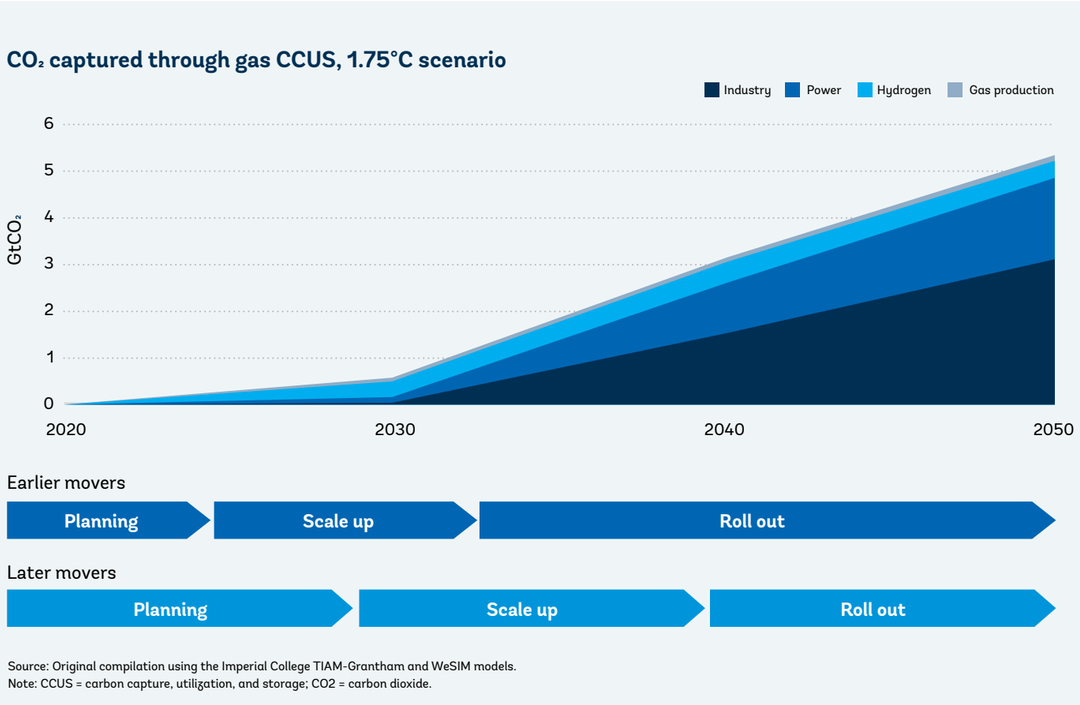
**Beyond a strong climate commitment, decisive action is needed to deliver CCUS, covering storage characterization, a legal and regulatory framework, and an enabling policy regime.** A number of barriers hinder deployment of CCUS at scale including uncertainty over $CO_2$ storage potential; regulatory uncertainty, including over the long-term liability of stored $CO_2$; limited

commercial incentives to deploy CCUS; challenges delivering CCUS capacity and public concerns over CCUS. These barriers must be addressed to unlock the opportunity for gas CCUS.

**Action will be needed across three phases of CCUS deployment: the planning, rollout, and scale-up phases.** These phases are described below and set against the deployment profile in the 1.75°C scenario developed in this study in Figure 32.

- **Planning:** The purpose of the planning phase is to carry out the necessary preparatory activities to ensure that CCUS can be delivered cost-effectively in the scale-up and rollout phases. In the planning phase, storage characterization and technoeconomic assessments are carried out to support policy decisions, the legal and regulatory environment is developed, and the funding needed for scale-up is allocated. Most countries are currently in the planning phase.
- **Scale-up:** The aim of the scale-up phase is to develop early commercial-scale CCUS projects and build out the transport and storage infrastructure to facilitate the rollout phase. At the same time, policymakers should develop and implement a funding mechanism to incentivize private sector investment in CCUS; and continue to assess the business case for CCUS in preparation for the rollout phase. A number of countries, such as the United States and Norway, are currently at the scale-up phase.
- **Rollout and consolidation:** The purpose of the rollout phase is to build a sufficient track record to access capital at reasonable market rates, and to build up a sustained CCUS industry supply chain capable of delivering sufficient installation rates. During this phase, an ongoing review of the funding mechanism will ensure it continues to deliver value for money. Toward the latter end of this phase, domestic CCUS is consolidated as a mature industry.

**Figure 32. Actions needed across three phases to achieve global abatement potential of gas CCUS**




Source: Original compilation using the Imperial College TIAM-Grantham and WeSIM models.
Note: CCUS = carbon capture, utilization, and storage; CO2 = carbon dioxide.



## 5.1 Planning phase

**In the planning phase, policymakers who envisage a role for natural must consider developing a strategy for CCS development and deployment, before achieving readiness for accelerated CCUS deployment.** The right level of investment in CCUS will emerge only after the role of CCUS on natural gas production and use in achieving national climate objectives is clarified. Underinvestment in CCUS could put national climate objectives at risk or necessitate reliance on more costly climate solutions. To avoid both these outcomes, policymakers, businesses, and investors require a degree of clarity on the need for CCUS on natural gas production and use.

**To support a strategic decision on the role of CCUS on natural gas production and use, policymakers should clarify the future role of natural gas with CCUS, and investigate $CO_2$ storage capacity. Clarity on the role of gas CCUS requires an understanding of the opportunities for gas CCUS to minimize the cost of meeting national climate objectives,** and a degree of confidence in the adequacy of domestic $CO_2$ storage potential to support the volumes of $CO_2$ capture. To achieve these conditions policymakers should carry out, firstly, a detailed economic assessment of the role of gas CCUS in meeting their countries' long-term climate targets, which considers the characteristics of hard-to-abate sectors and the relative costs of addressing these with gas CCUS and alternative technologies; and, secondly, a high-level storage assessment, which includes a desk-based estimate of all potential storage resources based on available data on geological formations.

**Once committed to delivering CCUS on gas production and use, policymakers should embed CCUS into the national mitigation strategy to align policy, business, and investor decisions.** CCUS requires coordination between government, businesses, and investors. Further, it is a highly capital-intensive technology and therefore investors need to have the confidence that CCUS will play an enduring role. A published strategy that articulates the role of gas CCUS in meeting national climate objectives, expectations for volumes of $CO_2$ captured across sectors, and firm plans to improve CCUS readiness would give policymakers, businesses, and investors a degree of clarity on the future role of gas CCUS, creating shared expectations and ensuring that private investment decisions are aligned with each other. The strategy should detail the role that gas CCUS will play across the main opportunities: industry, power generation, low-carbon hydrogen production and use, and natural gas production. Finally, it should identify the skills that will be needed to deliver CCUS in line with national climate objectives, assess the adequacy of current skills in the national workforce, and set out how any skills gap will be bridged through capacity building.

**To realize strategic objectives for low-carbon hydrogen production and use, policymakers should also publish a clean hydrogen strategy.** Like CCUS, hydrogen also requires coordination, particularly to align decisions on hydrogen production, storage, transportation, and end use. An overarching clean hydrogen strategy will support the growth in supply and demand for clean hydrogen overall, including supply and demand for low-carbon hydrogen. It should set out the role that clean hydrogen will play in the power, industry, transportation, and building sectors, and in the production of ammonia and methanol. The strategy should also address public acceptability, providing information on the safety of hydrogen and setting out how regulations, codes, and standards will be developed to enable its use.

**In line with the role of CCUS on natural gas production and use in the national mitigation strategy, policymakers should achieve readiness for accelerated CCUS deployment with pilot projects, storage characterization, development of a legal and regulatory framework, and enabling policy.**

- **Pilot projects to build institutional capacity.** As detailed in Section 2.8, policymakers may lack the capacity to deliver CCUS, particularly in developing and emerging economies. Development of initial pilot projects in countries that have yet to deploy CCUS can help build institutional capacity among policymakers, the oil and gas sector, the CCUS supply chain, and the financial sector to cooperate in delivery of CCUS.
- **Create a detailed assessment of $CO_2$ storage capacity.** The detailed assessment should build on the preliminary storage assessment carried out to support the strategic decision on the role of gas CCUS and include physical site-specific testing of storage capacity and injection performance.
- **Develop an effective legal and regulatory framework for CCUS.** A clear and efficient legal and regulatory framework governing all aspects of a CCUS project is needed to support project

developers evaluate and deliver a CCUS project. An effective framework must cover regulatory approval, the main phases of the CCUS project life cycle (construction, operation, and closure), siting and environmental and social assessment, and the allocation of liability for closure and accidental releases of $CO_2$. Further, limiting private investors' exposure to any long-term storage liabilities (such as by sharing liabilities between the project and the state and the transfer of liabilities to the state after a specified period beyond closure of the storage site) may be needed to unlock the business case for CCUS projects. Such liability management mechanisms would be contingent on the operator adhering to all legal and regulatory requirements and would be declared void in case of negligence. Further, clear and comprehensive technical standards governing the design and specifications of CCUS facilities and infrastructure are needed to ensure an adequate level of technical, safety, and environmental performance.

- **Plan strategic clusters to minimize the cost of delivering CCUS.** If several large emitters are located close together, for example, in industrial areas, CCUS clusters enable shared transport and storage infrastructure, minimizing the cost of delivering CCUS. Policymakers should plan these clusters at the outset, to ensure that CCUS can be delivered at least cost, and to signal to new businesses where they should locate in order to benefit from lower-cost transport and storage infrastructure.
- **Allocate capital for direct investment in early-stage capture projects and infrastructure in the government budget.** The capital cost premium of CCUS can be funded directly by government or by the private sector through market-based funding mechanisms to provide investment incentives and address barriers to delivery, while allowing private firms to make investment decisions. However, the currently limited role of liberalized markets in the energy sector of many developing and emerging economies would make implementation of a market mechanism for CCUS more challenging. As a result, in many countries direct public investment in capture projects and transportation and storage infrastructure may be needed initially to secure delivery of early-stage gas CCUS. As CCUS projects are large, capital-intensive projects, policymakers will need to ensure that the government budget incorporates such investment in advance.

**For constrained gas users, policymakers will need to carefully consider the role of CCUS and alternatives.** Constrained gas users such as Japan and Vietnam, that will face high gas prices and limitations in available gas supply, will need to carefully assess the cost-competitiveness of CCUS on natural gas relative to alternative decarbonization solutions and aim to use CCUS on natural gas only where these alternative solutions are not available and/or not cost-effective.

## 5.2 Scale-up phase

**In the scale-up phase, policymakers should provide financial support for initial CCUS projects, and develop effective CCUS funding mechanisms.**

- **Make public investments in early-stage capture projects and infrastructure.** Having secured the allocation of capital to finance early-stage capture projects and infrastructure in the government budget in the planning phase, policymakers will move ahead with the investment and contract their delivery in the scale-up phase.
- **Develop and implement a CCUS funding mechanism.** Although direct public investment in capture projects and transportation and storage infrastructure may be needed initially, over the longer term, market mechanisms offer a number of advantages. Market mechanisms allow private sector investment, relieving pressure on government budgets, reducing the need for the government to take on risks that are better managed by the private sector, and leveraging information held by the private sector on firm-specific gas CCUS costs. Box 18 describes a range of possible CCUS funding mechanisms and their advantages and disadvantages. Policymakers should evaluate the range of available options and define a funding mechanism appropriate to national circumstances. International funding mechanisms may also emerge, as countries cooperate through carbon markets and other initiatives to reduce GHG emissions; policymakers should identify opportunities to leverage such funding mechanisms to deliver gas CCUS domestically.



### Box 18. Market-based CCUS funding mechanisms

- **Obligation with CCUS certificates.** Emitters or fuel suppliers are obligated by law to ensure a certain amount of $CO_2$ is captured and stored. Certificates are awarded for storage and can be used to meet the obligation and traded freely. The obligation could be price-based (a fixed cost per ton of $CO_2$ from extracted oil) or quantity-based (a quota on allowable oil extraction) and could be levied at the point of production, or the point of export.
  - Advantages: Incentivizes delivery of least-cost CCUS projects; minimizes costs and risk held by government.
  - Disadvantages: Careful design needed to limit private sector cost burden and price volatility; needs a liquid market to function effectively.
  - Existing applications: Tradable obligations have a strong track record in securing high CAPEX renewable energy investments in a number of countries. Examples include the Renewables Obligation in the United Kingdom and the Renewable Energy Certificates in Texas.
- **Emission performance standards (EPS) with CCUS certificates.** An EPS sets minimum emission standards, either at a project or portfolio level, by which emitters must abide. The tradeable certificates function similarly to the obligation scheme and can be used to meet the standard.
  - Advantages: Incentivizes delivery of least-cost CCUS projects; minimizes cost and risk held by government.
  - Disadvantages: Could place large risks on the private sector.
  - Existing applications: Emissions performance standards for electricity generators have been implemented in a number of countries, including the United Kingdom and Norway, though these have not been accompanied by tradable certificates. Development of the Boundary Dam Carbon Capture project in Canada was in part stimulated by an emissions performance standard.
- **Tradable tax credits.** The tax liability of firms is reduced if they perform CCUS. Credits can be provided for stored carbon and also for capital investment.
  - Advantages: Minimizes price risk to developers; incentivizes delivery of least-cost CCUS projects.
  - Disadvantages: Involves inherent policy risk given the scope for government to renege on commitments; may place large costs and risks on the government.
  - Existing applications: The 45Q Tax Credits in the United States offers credit value of $\$35/tCO_2$ for projects with EOR and $\$50/tCO_2$ for projects with dedicated storage.
- **Emission trading schemes (ETS).** A cap on total emissions is set and tradable emissions allowances are distributed to participating firms. The price of allowances should approximate the marginal cost of abatement technologies needed to meet the emissions cap.
  - Advantages: Already well established and proven in some regions; incentivizes delivery of least-cost CCUS projects.
  - Disadvantages: May not provide adequate price signal; could place large risks on the private sector; could cause uncertainty and potential volatility of future allowance prices.
  - ETSs have been implemented in a number of jurisdictions, including the European Union, California, and Quebec. To date, prices of emissions trading schemes have not been high enough to deploy CCUS.

**To support low-carbon hydrogen, policymakers should also ensure that conditions for the deployment of clean hydrogen are adequate to deliver the objectives of the national hydrogen strategy.** Conditions to support deployment of clean hydrogen include incentives, a policy framework to minimize life-cycle emissions, and management of public opinion:

- Policy options to deliver clean hydrogen include carbon pricing, price support for hydrogen-based technologies, emissions performance standards in the power and industry sectors, phase-out policies in the building and road transport sectors, and fleet average $CO_2$ standards in the heavy transport and shipping sectors. A degree of public funding may also be required initially to support development of hydrogen transmission, storage, and vehicle fueling infrastructure, and research and development.
- To support low-carbon hydrogen to play a role in the clean hydrogen mix, policymakers will need to incentivize the reduction of upstream emissions from natural gas, including methane and $CO_2$ emissions occurring during natural gas extraction. Further, so that low-carbon hydrogen is able to compete internationally and meet importer requirements, policymakers will need to implement rigorous and transparent certification standards, and carry out associated monitoring and enforcement to ensure these standards are met.[46]
- Policymakers will also need to manage public opinion on hydrogen through clear and effective communication on the safety and environmental risks associated with hydrogen production and use.

**For gas exporters looking to export low-carbon hydrogen, policymakers and businesses should secure bilateral agreements on hydrogen supply.** The market for clean hydrogen is expected to remain immature, with a small number of countries producing and importing hydrogen at scale, over the near term. As a result, producers face large risks due to reliance on a small number of importers, and importers face large risks due to reliance on a small number of producers. Until a more mature clean hydrogen market develops, with many countries producing and importing hydrogen at scale, risks can be minimized through bilateral agreements. If policymakers are able to secure an agreement for hydrogen supply to a country that wishes to expand its use of hydrogen as a fuel source, hydrogen producers can be more certain of export revenues, and the business case to invest in hydrogen production. Examples of such agreements are already emerging: in September 2020, Australia and Germany signed a bilateral agreement to establish a hydrogen supply chain between the two countries;[47] in November 2020, Portugal and the Netherlands strengthened existing bilateral cooperation by agreeing to develop a strategic hydrogen import-export chain;[48] and in July 2021, Chile and Germany expanded their 2019 energy partnership by signing a letter of intent for a bilateral alliance on hydrogen production and trade.[49]

**A market assessment of international clean hydrogen demand should precede large-scale investment decisions.** The market for clean hydrogen (and the use of hydrogen-based fuels such as ammonia) is growing, and a number of countries are developing hydrogen production infrastructure for export. Low-carbon hydrogen exporters will compete with each other and with renewable hydrogen exporters for this market. A detailed market assessment would reduce the risks of investing in low-carbon hydrogen production and export capacity.

**Policymakers and businesses in countries with limited $CO_2$ storage capabilities and their neighbors, should work to secure bilateral agreements on $CO_2$ storage.** Some countries may face challenges in developing and operating low-cost $CO_2$ storage sites. In some countries, storage capacity may be limited relative to total national emissions, may be costly to develop, or may be difficult to develop due to technical challenges or environmental impacts. Further, some countries with limited financial resources and technical capabilities in geological engineering may face challenges in developing the technical capabilities to develop and operate such sites. For these countries, exporting $CO_2$ to neighboring countries with a comparative advantage in exploiting low-cost $CO_2$ storage sites may offer the most cost-effective route to gas CCUS. As with low-carbon hydrogen, bilateral agreements for $CO_2$ export and storage with a neighbouring country with ample low-cost storage resources and the technical capacity to exploit them can provide the necessary certainty over the future availability of $CO_2$ storage. An example of such a cross-border opportunity is emerging at the Northern Lights $CO_2$ storage project off Norway's west coast. Set to commence full-scale operations by 2024, the project will offer storage services to Norwegian emitters, as well as companies across Europe, becoming the world's first cross-border, open source CCUS infrastructure network.[50]

46 The European Union is currently developing proposals for a certification scheme for clean hydrogen and other fuels. On December 15, 2021, the European Commission adopted a set of legislative proposals to support renewable and low-carbon gases including hydrogen, including certification of these fuels with a threshold for greenhouse gas emissions savings of at least 70 percent.
47 Euractive (2020): https://www.euractiv.com/section/energy-environment/news/hydrogen-trade-hopes-boosted-by-australia-germany-deal/.
48 Government of the Netherlands (2020): Portugal and the Netherlands strengthen bilateral cooperation on renewable hydrogen | News item | Government.nl.
49 Reuters (2021): Germany and Chile sign accord to boost hydrogen cooperation | Reuters.



## 5.3 Rollout phase

**Provided the business case remains sound, policymakers should continue to support the market conditions for CCUS deployment.** The scale-up phase will have laid the groundwork for the rollout phase, through development of a critical mass of transport and storage infrastructure serving a number of key CCUS clusters, implementation of a funding mechanism to support long-term deployment, development of a mature domestic CCUS supply chain, a pipeline of new projects that keeps pace with new investments in power and industrial facilities, and a flow of investment to finance these projects at reasonable market rates. Throughout the rollout phase, policymakers will need to oversee the extension of gas CCUS to higher-cost applications, such as end-use sectors such as iron and steel and refining where capture rates are lower, or decarbonization of industrial facilities more distant from $CO_2$ storage sites.

**Policymakers should also ensure the funding mechanism continues to deliver value for money.** Both price-based mechanisms (such as taxes or subsidies) and quantity-based mechanisms (such as ETSs) can result in inefficient patterns of spending or investment over time, as circumstances change. For example, funding mechanisms such as CCUS obligations or tax credits require a public sector judgment on the level of obligation or subsidy, and may fail to reflect the cost or value of CCUS if CCUS costs decrease faster than expected, or if international and domestic demand for CCUS are higher or lower than expected. An ongoing review of the funding mechanism will allow adjustment of the financial support provided to CCUS to reflect changes in its costs or in demand and minimize unnecessary public or private expenditure.

50 Northern Lights CCS (2021): https://northernlightsccs.com/what-we-do/.

## 5.4 Role of international financial institutions

**CCS on natural gas is likely to be relevant in developing and emerging economies, in particular large gas users and gas exporters, so international financial institutions such as the World Bank, Asian Development Bank, and Green Climate Fund have a crucial role to play in supporting them to deliver CCS in order to achieve the Paris Agreement goals.** Globally, this analysis estimates that the overall application for gas CCUS could be around 5 $GtCO_2$ in a 1.75°C scenario. Of this, around 75 percent, is estimated to arise in developing and emerging economies. However, readiness to deploy gas CCUS in developing and emerging economies is particularly low. Compared to advanced economies, developing and emerging economies typically face poorer characterization of storage assessment, legal and regulatory frameworks that are less suited for gas CCUS, and a less developed policy regime to incentivize deployment of CCUS on natural gas. Further, developing and emerging economies typically possess more limited financial resources and technical capabilities than the advanced economies that are at the forefront of progress with readiness for CCUS, and many development priorities compete for these financial resources. Therefore, international financial institutions have a vital role in supporting these economies to deploy CCUS. The World Bank's Climate Action Plan sets out how it will aim to address climate change as part of its wider mission to reduce poverty and build shared prosperity in developing countries. Box 19 describes the World Bank Climate Change Action Plan.

**While this study focuses on the role of CCUS on natural gas production and use in contributing to the objectives of the Paris Agreement and net zero emissions, it carries multiple additional benefits relevant to the mission of international financial institutions such as the World Bank:**

- **CCUS can reduce the cost burden of decarbonization for countries with gas resources.** The energy transition poses challenges for countries that are heavily dependent on natural gas resources for economic activity, government revenues, and jobs. CCUS on natural gas offers an opportunity for such countries to reduce their GHG emissions while continuing to

generate vital revenues and potentially participate in new markets for clean hydrogen, avoiding the social and economic damage of a more abrupt transition.

- **CCUS can provide a long-term source of employment.** These employment opportunities may be particularly valuable for countries with mature oil and gas industries, which may see a contraction of activity in this sector, as global demand for these commodities declines or if domestic reserves decline. As the CCUS sector requires a skill base similar to that of the oil and gas industry, this sector could provide a viable source of long-term employment for workers currently employed in oil and gas.
- **CCUS can support the competitiveness of energy-intensive industry, while these sectors undertake deep decarbonization.** Energy-intensive industries are generally hard-to-abate sectors with high costs of decarbonization and are exposed to substantial international competition. Reliance on costly mitigation solutions in this sector can increase product prices and decrease international competitiveness, leading to reduced profitability, and potentially industry closures and job losses. Failing to decarbonize these sectors could potentially lead to similar outcomes if trading partners implement carbon border adjustment mechanisms to support their own industrial decarbonization efforts. In some sectors and countries, CCUS on natural gas use may be the least-cost decarbonization solution, and may be able to support national industries to remain competitive while decarbonizing.

### Box 19. World Bank Climate Change Action Plan

The World Bank Climate Action Plan aims to reduce emissions, strengthen adaptation, and align financial flows with the Paris Agreement objectives by delivering climate finance to developing economies. The plan's integrated approach goes beyond investment in individual green projects, seeking to guide sustainable economic recovery from the COVID-19 pandemic, in alignment with national climate objectives. To achieve this, the World Bank will:

- **Deliver major increases in climate finance to emerging economies.** The plan will increase climate finance by an average of 35 percent. Additionally, at least half of International Development Association (IDA) and International Bank for Reconstruction and Development (IBRD) financing will support adaptation to the challenges of climate change.
- **Prioritize high-impact actions that generate transferrable knowledge.** Deploying the Country Climate and Development diagnostic tool, the World Bank will ensure that priority actions deliver lessons and technologies that inform future investments, enabling the wider international community to benefit from individual World Bank engagements.
- **Increase support for countries updating their NDCs.** The plan will raise financial support for countries revising their NDCs in line with the Paris Agreement objectives. Subsidies for GHG emissions taxes will be lowered to incentivize abatement.
- **Mobilize private climate finance.** The plan will accelerate the development of carbon markets and other private climate financing mechanisms. The world's poorest countries will receive IDA support toward global public goods.
- **Prioritize action in key systems.** Energy, land use, transport, manufacturing, and city sectors will be supported to deliver a "just transition" as they shift to low-carbon pathways. The protection of biodiversity and natural capital is of high priority.
- **Align all World Bank financing flows with the Paris Agreement objectives.** All IDA and IBRD operations, as of July 2023, will be aligned to meet the Paris Agreement targets. Private sector development operations will fully align by 2025.

**Within the plan, CCUS is identified as a necessary tool to deliver emissions reductions in line with the Paris agreement objectives, while ensuring a just transition.** The plan recognizes the heightened financial, social, and macrostructural risks associated with the energy transition in countries currently dependent on unabated fossil fuel use. As such, the plan will promote CCUS initiatives as viable and sustainable solutions to improving climate and development outcomes, recognizing the value of CCUS in reducing exposure to carbon lock-in and stranded assets. Further, in prioritizing action in key systems, the plan identifies CCUS as an important lever for decarbonization of the power sector.

**In the case of the World Bank Group, several organizations could play a strong role in supporting CCUS on natural gas production and use:**

- The **International Bank for Reconstruction and Development** (IBRD) and **International Development Association** (IDA) provide grants and loans to low- and middle-income countries. The IBRD and IDA are well positioned to provide financial services to the governments of low- and middle-income countries seeking to invest in gas CCUS to meet climate targets. The IBRD and IDA could also support CCUS capacity building and technical knowledge-sharing in developing economies through technical assistance, advisory services, and analytics.
- The **International Finance Corporation** (IFC) focuses on delivering sustainable private sector finance to developing economies. The IFC could facilitate the deployment of gas CCUS by providing investment to relevant private sector organizations in emerging economies.
- The **Multilateral Investment Guarantee Agency** (MIGA) seeks to promote foreign direct investment through offering noncommercial risk insurance to investors and lenders. MIGA could support CCUS activities by providing political risk insurance to CCUS project investors in emerging economies.

**The World Bank has already begun to support developing economies in planning for and delivering CCUS.** The World Bank CCS Trust Fund has provided financial support to developing economies for the development of CCS regulation, the characterization of $CO_2$ storage resources, and the planning and implementation of roadmaps to the deployment of CCS, since 2009. The World Bank CCS Trust Fund is also supporting CCUS pilot activities in Mexico and South Africa. As of 2017, the fund had supported CCS operations (or was developing programs) in nine countries. Further, the World Bank, in contributing to the Joint Report on Multilateral Development Bank Climate Finance, identified CCS as an activity eligible for climate mitigation finance.



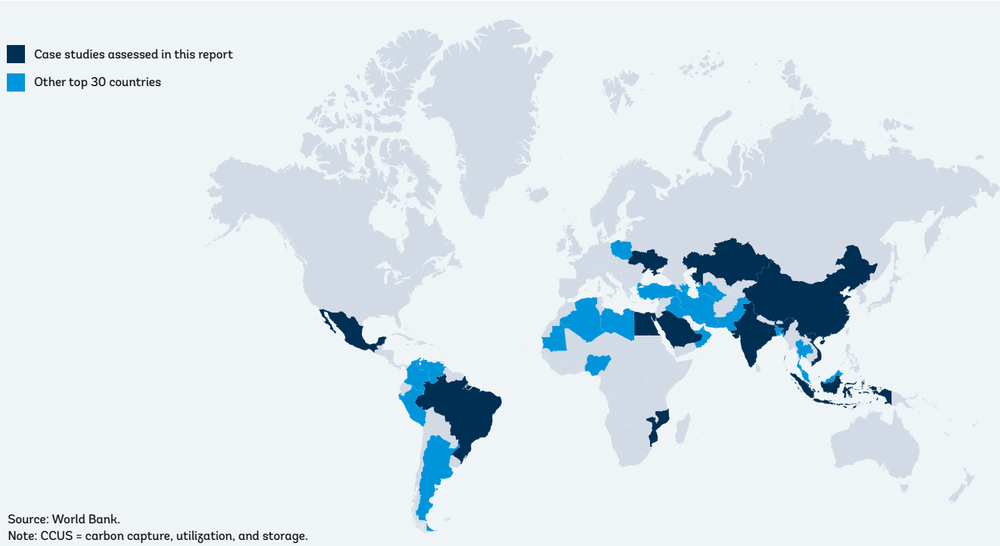
**A large number of countries could benefit from the support of international financial institutions to deliver CCUS on natural gas production and use.** This study has identified 30 countries eligible for World Bank lending as potentially having the need for gas CCUS. Figure 33 shows these 30 countries, and the 11 countries chosen as case studies separately.

**In the early stages of the planning phase, international financial institutions could support policymakers to make a strategic decision on the role of CCUS to decarbonize natural gas production and use.** Policymakers will need to carry out a detailed economic assessment of the role of CCUS in meeting its long-term climate target, considering in detail the characteristics of hard-to-abate sectors and the relative costs of addressing these with CCUS and alternative technologies. International financial institutions could provide policymakers carrying out this assessment with both technical assistance and financial support.

**In the later stages of the planning phase, international financial institutions could support policymakers in achieving readiness for accelerated CCUS deployment.** Policymakers may require financial support and technical assistance to carry out a detailed assessment of $CO_2$ storage capacity, to develop effective legal, regulatory, and institutional frameworks for CCUS, and build capacity to manage and monitor its deployment.

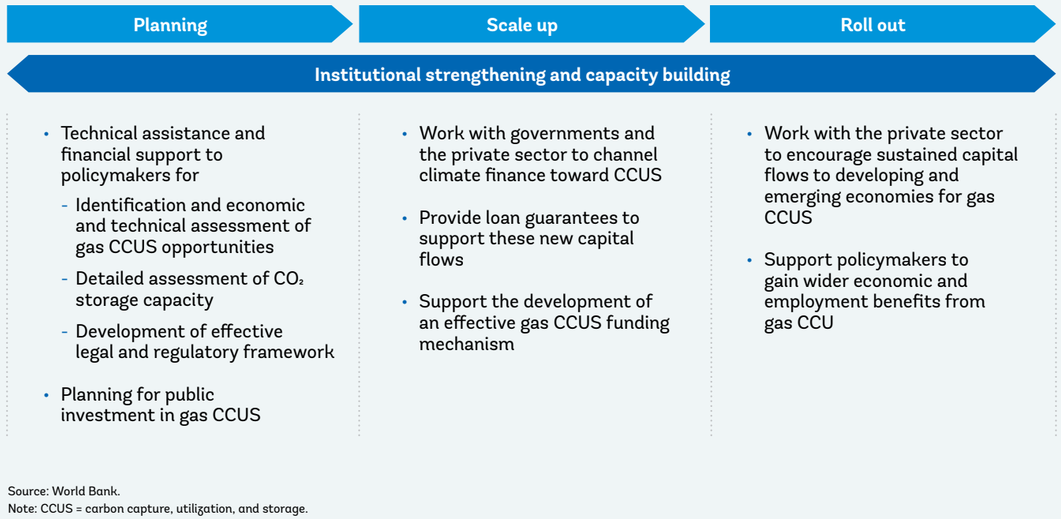
**In the scale-up phase, international financial institutions could support policymakers and businesses to secure the necessary financing and to develop an effective funding mechanism.** CCUS is a highly capital-intensive technology and will require very substantial investment to deploy at scale. Financing CCUS exclusively through public sector investment, particularly in developing and emerging economies, would likely put considerable strain on government budgets, and require the government to take on commercial risks that are better managed by the private sector. The World Bank's Climate Change Action Plan commits to providing major increases in climate finance and to catalyse and mobilize private capital for climate action. Ensuring adequate private capital flows for developing and emerging economies, for gas CCUS and more widely, would reduce financing barriers and enable accelerated deployment. International financial institutions could work with governments and the private sector to channel climate finance toward CCUS, and through MIGA provide loan guarantees to support these new capital flows. Further,

**Figure 33. Thirty countries eligible for World Bank lending are identified as having strong opportunities for gas CCUS**




Source: World Bank.
Note: CCUS = carbon capture, utilization, and storage.

**Figure 34. Support from international financial institutions could occur at the planning, scale-up, and rollout stages**




Source: World Bank.
Note: CCUS = carbon capture, utilization, and storage.



international financial institutions could provide capacity building support and direct technical assistance to policymakers to develop an effective CCUS funding mechanism, to underpin the business case for private sector investment.

**In the rollout phase, international financial institutions could work with the private sector to encourage sustained capital flows to developing and emerging economies for CCUS on natural gas production and use.** While in the scale-up phase developing and emerging economies will need access to climate finance to support the deployment of early-stage gas CCUS projects and infrastructure, they may not be able to secure access to adequate levels of climate finance to support wider deployment in the rollout phase. In this phase, deployment levels are likely to be significantly higher, while the supply of climate finance will be limited, and countries and technologies will compete for this scarce supply. For the large-scale investment necessary to support large-scale deployment of CCUS on natural gas production and use in the rollout phase, private sector capital is likely to be needed. The World Bank's Climate Change Action Plan commits to catalyse and mobilize private capital for climate action. Ensuring private capital flows for developing and emerging economies, for gas CCUS and more widely, would reduce financing barriers and enable  accelerated deployment.

International financial institutions could also play a role in promoting international cooperation in CCUS. International cooperation can improve access to technical, operational, and managerial knowledge on CCUS on natural gas production and use and low-carbon hydrogen in developing and emerging economies, building capacity to deliver CCUS at least cost, and can support development of common international standards for lower-carbon natural gas.

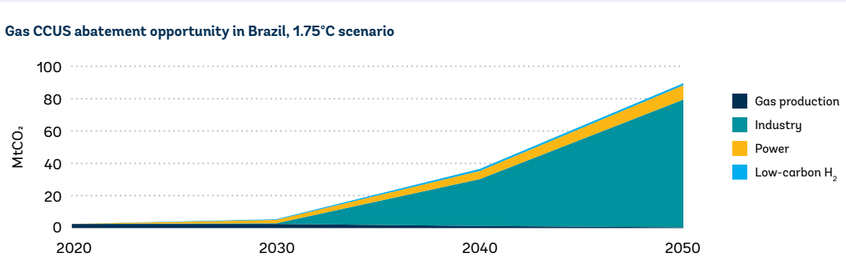
**Through these actions, policymakers and international financial institutions can substantially accelerate the deployment of CCUS on gas production and use, increasing the likelihood of achieving national and global emissions goals.** This section has identified actions for policymakers to accelerate deployment of gas CCUS and enabling actions for international financial institutions to support achievement of this objective.

- **Policy action is needed across three key phases of CCUS deployment: planning, scale-up, and rollout.** In the planning phase, policymakers who envisage a role of natural must then also develop a srtrategy for CCUS development and deployment, and then complete the planning phase by ensuring adequate readiness for CCUS, planning strategic CCUS clusters, allocating funding, and delivering early-stage transport and storage infrastructure. Once committed to delivering CCUS on natural gas production and use, policymakers should embed CCUS and natural gas decarbonization into the national mitigation strategy to align policy, business, and investor decisions. To realize strategic objectives for low-carbon hydrogen production and use, policymakers should also publish a clean hydrogen strategy. In the scale-up phase, policymakers could develop and implement a CCUS funding mechanism and create conditions for the first CCUS project in strategic clusters. In the rollout phase, policymakers could extend their support for CCUS to drive widespread deployment, while adjusting the funding mechanism as necessary to ensure it continues to deliver value.
- **International financial institutions such as the World Bank and the Asian Development Bank have a vital role in helping these economies to deploy CCUS.** This study has identified 30 countries eligible for World Bank lending as having strong opportunities for CCUS on natural gas production and use. International financial institutions could play a vital role in supporting policymakers in delivering CCUS. In the planning phase, international financial institutions could provide technical assistance and financial support with energy system planning and assessing $CO_2$ storage capacity, developing the legal, regulatory, and institutional frameworks for CCUS, supporting capacity building, and creating the conditions for first CCUS pilot projects. In the scale-up phase, international financial institutions could work with governments and the private sector to channel climate finance toward CCUS, provide loan guarantees to support these new capital flows, and provide capacity building support and direct technical assistance to policymakers to develop an effective CCUS-funding mechanism. Finally, in the rollout phase, international financial institutions could work with the private sector to encourage sustained capital flows to developing and emerging economies for CCUS, and help policymakers to gain wider economic and employment benefits from this technology.

These actions for policymakers and international financial institutions form the basis for the delivery roadmap for CCUS on natural gas production and use developed in this study.

# 6 Country case studies

## 6.1 Brazil

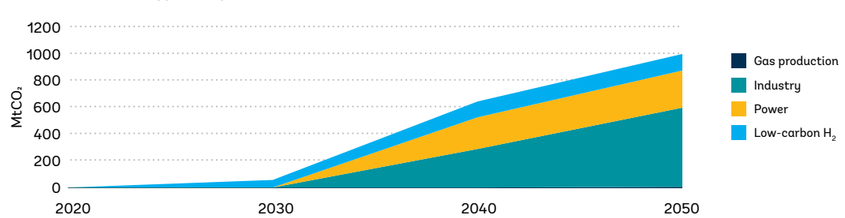
| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Brazil is estimated in this study to have the potential to mitigate up to 17 percent of emissions forecast under a baseline scenario by 2050, with the greatest opportunity estimated to arise in industry.** CCUS at the Santos Basin offshore gas production facility currently captures 0.7 $MtCO_2$/year, or <1 percent of present-day emissions in the country. This study finds gas CCUS could contribute a total of 90 $MtCO_2$ in emissions reductions per year by mid-century in a 1.75°C scenario, or 17 percent of the 523 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. CCUS with industrial gas use captures 79 $MtCO_2$ in 2050, or 88 percent of the total national CCUS abatement opportunity. More limited but important opportunities emerge in gas power generation (9 $MtCO_2$), natural gas production (roughly 1 $MtCO_2$), and low-carbon hydrogen production and use (roughly 2 $MtCO_2$). Low-cost applications in gas production and ammonia and methanol production could account for 56 percent of Brazil's gas CCUS abatement opportunity by 2030, helping facilitate the near-term deployment of gas CCUS in the country.<br><br>**Gas CCUS abatement opportunity in Brazil, 1.75°C scenario**<br><br> |
| **Progress to date** | **Brazil already deploys CCUS in gas production and has relevant industry experience in EOR.** Since 2011, Petrobras has deployed CCUS at the Santos Basin offshore gas production facility for EOR. The project will have stored 40 $MtCO_2$ by 2025. Petrobras has further EOR experience at the Miranga $CO_2$ injection project, which stores $CO_2$ emissions from fertilizer production. |
| **Storage readiness** | **Brazil likely has access to substantial $CO_2$ storage volumes, sufficient to contain the country's industry and power emissions for many years.** Emissions from industry, power generation, and heat totalled 178 $MtCO_2$ in 2019. The Centre of Excellence in Research and Innovation in Petroleum, the Ministry of Science, and Rystad Energy, have independently conducted high-level desk studies of $CO_2$ storage capacity in Brazil, indicating potential storage volumes of 300–2,000 $GtCO_2$. This implies theoretical capacity for Brazil to store current industry, power, and heat emissions for over 1,600 years. |
| **Cost of capture** | **There are low-cost opportunities which can help facilitate the near-term deployment of gas CCUS in Brazil.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 2.5 $MtCO_2$ and 0.7 $MtCO_2$/year respectively by 2030. This represents 56 percent of Brazil's total near-term gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, low-cost applications represent roughly 2 percent of Brazil's total gas CCUS abatement opportunity.<br><br>Moderate- to high-cost opportunities could abate a further 88 $MtCO_2$/year by 2050. Further, moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 88 $MtCO_2$/year by 2050, or 98 percent of the country's total gas CCUS abatement opportunity by mid-century. |

| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **There are significant opportunities to store $CO_2$ captured in power and industry with only a low infrastructure investment.** 33 percent of power generation emissions are generated within 100 km of potential storage sites, implying a significant volume of emissions could be captured and transported to storage sites in Brazil with a low infrastructure investment. moderate infrastructure developments would be required to transport and store captured $CO_2$, on average. In industry, 23 percent of emissions are generated within 100 km of potential storage sites, implying that while significant low infrastructure CCUS opportunities exist, requirements are likely to be relatively higher, on average.[51] |
| **EOR potential** | **The proximity of power and industry emissions to potential EOR sites implies significant quantities of $CO_2$ could generate revenues from storage, with only a low infrastructure investment.** Brazil likely has significant potential to exploit EOR, with Rystad Energy identifying roughly 6 $GtCO_2$ of injection potential in the country. 29 percent of power generation emissions and 17 percent of industry emissions are generated within 100 km of potential EOR sites. These opportunities to exploit EOR can be achieved with only a low infrastructure investment.[52] |
| **Legal and regulatory environment** | **Regulation of CCUS in Brazil leans heavily on existing oil and gas legislation.** As the majority of Brazil's current $CO_2$ injection projects relate to EOR, projects are typically governed by oil and gas industry regulation. As yet, this framework does not establish long-term liability over stored $CO_2$. In 2011, CCUS regulation was proposed, but not approved. |
| **Policy environment** | **Despite strong climate ambition, Brazil has not implemented carbon pricing mechanisms to incentivize CCUS deployment.** Brazil's NDC indicates a desire to reach net zero by 2060. Within this context, the country hopes to reduce emissions to 37 percent and 43 percent of 2005 levels by 2025 and 2030, respectively. At the COP26 international climate summit, Brazil announced its intention to reduce emissions to 50 percent of 2005 levels by 2030, while bringing forward the net zero target to 2050. Carbon pricing initiatives in the country are nascent, with a voluntary ETS covering only 29 firms. It should be noted that the firms included in Brazil's recent ETS simulation represent a relatively modest share of total emissions in the country. An oil and gas industry tax credit system provides one potential source of public funding for CCUS. |
| **Stakeholder engagement** | **While stakeholders in Brazil recognize the potential role of CCUS in the climate transition, this is not yet supported by a formal CCUS strategy.** Interviews conducted for the present study suggest that key stakeholders in Brazil are in consensus that CCUS has a role to play in the country's wider mitigation pathway, despite no formal government strategy having been established at time of writing. The large, state-owned firm, Petrobras, currently acts as the primary driver of CCUS project development.[53] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; ETS = emissions trading system; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

51 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
52 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
53 Information obtained through consultation with stakeholder at the University of Sao Paulo Institute of Energy and Environment. Stakeholder's research focus surrounds legislation, regulation, and policies to facilitate Brazil's transition to a low-carbon economy, including through deployment of technologies such as CCUS.

## 6.2 China

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS is estimated in this study to have the potential to mitigate up to 9 percent of emissions forecast under a baseline scenario in China by 2050, with the greatest opportunities estimated to emerge in industry and power generation.** Large-scale CCUS facilities currently capture roughly 0.6 $MtCO_2$/year, or <1 percent of present-day emissions in the country. This study finds gas CCUS in China could contribute a total of 997 $MtCO_2$/year in emissions reductions by mid-century in a 1.75°C scenario, or 9 percent of the roughly 11.6 $GtCO_2$ expected to be emitted in 2050 under a baseline scenario. The greatest opportunity emerges in industry, where gas CCUS could abate 586 $MtCO_2$/year by 2050, or 59 percent of the total national abatement opportunity. CCUS with gas power generation also presents a substantial abatement opportunity, capturing 279 $MtCO_2$/year, by 2050. CCUS with natural gas production and CCUS with low-carbon hydrogen production and use could abate 10 $MtCO_2$ and 122 $MtCO_2$/year by 2050 respectively. Low-cost applications in gas production and ammonia and methanol production could account for 98 percent of China's gas CCUS abatement opportunity by 2030, helping facilitate the near-term deployment of gas CCUS.<br><br>**Gas CCUS abatement opportunity in China, 1.75°C scenario**<br><br> |
| **Progress to date** | **China has deployed CCUS at a range of pilot and demonstration facilities, and the country's large-scale pipeline is growing.** As of 2021, 35 CCUS projects had been delivered. The majority of these projects are at demonstration and pilot facilities and have been publicly financed by the Chinese government. CNPC's Jilin Project captures 0.6 $MtCO_2$/year at a natural gas processing facility and is set to be joined by multiple large-scale projects over the period to 2030. These planned projects are likely to cover a range of industries, including power generation and chemical production. |
| **Storage readiness** | **Emissions in China are high, though estimated storage capacity is likely sufficient to sequester them for roughly 50 years.** Emissions from industry, power generation, and heat totalled 8.3 $GtCO_2$ in 2019. Many high-level studies have been conducted in China to estimate storage potential, with some supported by detailed wellhead analysis. However, uncertainty remains over ultimate storage capacity, with estimates ranging from 400–3,000 $GtCO_2$. Such volumes imply adequate potential to store current domestic emissions for 48 to 380 years. |
| **Cost of capture** | **There are low-cost opportunities, which can help facilitate the near-term deployment of gas CCUS in China.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 3.4 $MtCO_2$ and 53 $MtCO_2$/year respectively by 2030. This represents roughly 98 percent of China's total gas CCUS abatement opportunity by 2030 and could help facilitate the near-term deployment of gas CCUS in the country. By 2050, 13 percent of China's gas CCUS abatement opportunity is achievable at low cost.<br><br>Moderate- to high-cost opportunities could abate a further 865 $MtCO_2$/year, by 2050. Further, moderate- to high-cost applications of gas CCUS in gas power generation and industry, could abate up to 865 $MtCO_2$/year by 2050, or 87 percent of the country's total gas CCUS abatement opportunity by mid-century. |

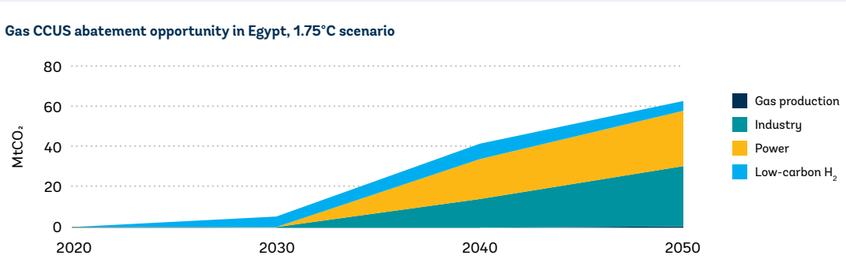


| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **The infrastructure requirements to store $CO_2$ captured from power generation and industry are likely to be moderate on average.** In China, 53 percent of power generation emissions are generated within 100 km of potential storage sites, implying over half the emissions from the sector could be captured and stored with a relatively low infrastructure investment. In industry, 50 percent of emissions are generated within such proximity, implying similarly low infrastructure requirements to transport and store captured $CO_2$, for a substantial quantity of emissions.[54] |
| **EOR potential** | **The proximity of emissions sources to potential EOR sites implies that only a low infrastructure investment would be required to generate revenues from storage activities for a significant share of industry and power emissions.** China likely has significant opportunities to exploit EOR, with Rystad Energy identifying roughly 19.3 $GtCO_2$ injection potential.31 percent of both power generation and industry emissions are generated within 100 km of potential EOR sites, implying that nearly a third of emissions from each sector could be used to exploit EOR with only a low infrastructure investment.[55] |
| **Legal and regulatory environment** | **CCUS activities are not currently regulated in China, but regulation is under development.** China does not currently have CCUS-specific regulation. Province-level laws are currently under development and are intended to provide specific regulation to govern the development and implementation of CCUS projects. |
| **Policy environment** | **China's policy environment increasingly provides incentives to invest in CCUS, though not yet at the scales required by the scenario developed for this study.** CCUS-specific policies are under development, aiming to provide standards, subsidies, and support for international cooperation in CCUS activities. China has a strong climate commitment, and an ETS has recently been established, covering 2,225 coal- and gas-fired power plants. When expanded to cover further industries, China's ETS will be the largest in the world, covering 14 percent of global combustion $CO_2$ emissions. However, carbon prices are low compared to established schemes such as the EU ETS and, as such,are not yet sufficient to drive a large-scale CCUS uptake. |
| **Stakeholder engagement** | **Stakeholder engagement toward delivering CCUS in China is relatively strong.** Stakeholder consultations conducted by the present study suggest government bodies such as the National Development and Reform Commission and the Ministry of Environmental Protection, and industry stakeholders, have historically aligned to successfully deliver multiple pilot and demonstration CCUS projects. Such engagement must continue for China to deliver the substantial pipeline of CCUS projects planned for development over the coming years, particularly at the larger scale required to meet climate targets.[56] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; ETS = emissions trading system; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

54 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
55 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
56 Information obtained through consultation with stakeholders representing the Asian Development Bank—with expertise in hydrogen, CCUS, and renewable energy technologies; and Tsinghua University's Institute for Carbon Neutrality (ICON)—with expertise on industrial emissions abatement, CCUS, and carbon-sink capacity.

## 6.3 Egypt

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Egypt is estimated in this study to have the potential to mitigate up to 24 percent of emissions forecast under a baseline scenario by 2050, with significant opportunities estimated to emerge in industry and power generation.** CCUS does not currently contribute to emissions reductions in Egypt. This study finds gas CCUS could contribute a total of 63 $MtCO_2$ in emissions reductions per year, by 2050, in a 1.75°C scenario, or 24 percent of the 259 $MtCO_2$ anticipated to be emitted by mid-century under a baseline scenario. The greatest abatement opportunity emerges in industry, capturing 30 $MtCO_2$/year by 2050, or 48 percent of the total national abatement potential. CCUS with gas power generation accounts for 27 $MtCO_2$ (44 percent) by mid-century. Low-cost applications in gas production and ammonia and methanol production account for 90 percent of Egypt's gas CCUS abatement opportunity by 2030 (5.2 $MtCO_2$). Such applications could help facilitate the near-term deployment of gas CCUS.<br><br>**Gas CCUS abatement opportunity in Egypt, 1.75°C scenario**<br><br> |
| **Progress to date** | **There are no existing or planned CCUS projects in Egypt to date.** No industry, power, or gas production CCUS projects are planned, either pilot or commercial. While some renewable hydrogen developments are planned, there are currently no low-carbon hydrogen projects in the country. |
| **Storage readiness** | **Egypt likely has sufficient storage volumes to sequester domestic emissions at current levels for many years.** Emissions from industry, power generation, and heat totalled 152 $MtCO_2$ in 2019. In 2009, the World Bank commissioned a consortium to carry out a high-level desk assessment of CCUS readiness in Egypt. This study estimates storage potential in the country to range from 85–600 $GtCO_2$, implying adequate capacity to store current emissions for over 560 years. Detailed analysis of storage resources supported by wellhead data is needed to improve storage readiness, and ultimately support large-scale deployment of CCUS. |
| **Cost of capture** | **There are low-cost opportunities, which can help facilitate the near-term deployment of gas CCUS in Egypt.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 0.2 $MtCO_2$ and 5 $MtCO_2$/year respectively by 2030. This represents 90 percent of Egypt's near-term gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost applications represent 6 percent of Egypt's total gas CCUS abatement opportunity.<br><br>**Moderate- to high-cost opportunities could abate a further 59 $MtCO_2$/year by 2050.** Further, moderate- to high-cost applications of gas CCUS in low-carbon hydrogen production, gas power generation, and industry, could abate up to 59 $MtCO_2$/year in Egypt by 2050, or 94 percent of the total gas CCUS abatement opportunity by mid-century. |

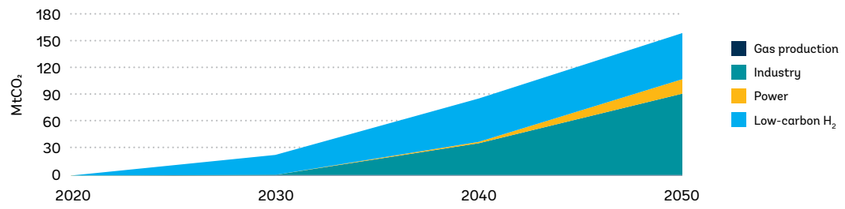


| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage**<br><br>**EOR potential** | **In Egypt, the infrastructure requirements to store $CO_2$ captured from power generation and industry are likely to be low.** In Egypt, 97 percent of power generation emissions are generated within 100 km of potential storage sites, implying low infrastructure developments would be required to transport and store captured $CO_2$, on average. In industry, 84 percent of emissions are generated within such proximity, implying similarly low infrastructure requirements to transport and store captured $CO_2$, on average.[57]<br><br>**In Egypt, the proximity of power and industry emissions to potential EOR sites implies relatively low infrastructure requirements to generate revenues from storage activities.** Egypt likely has significant opportunities to exploit EOR, with roughly 2 $GtCO_2$ of injection potential identified by Rystad Energy. In Egypt, 88 percent of power generation emissions and 76 percent industry emissions are generated within 100 km of potential EOR sites, implying relatively low infrastructure requirements to exploit EOR using emissions from these sectors, on average.[58] |
| **Legal and regulatory environment** | **Egypt does not currently regulate CCUS activities.** No regulation specifically governing CCUS activities currently exists in Egypt. While in other countries CCUS projects have been governed by oil and gas industry regulation, no such projects have been conducted in Egypt to date. |
| **Policy environment** | **While Egypt's policy environment does not currently support the at-scale deployment of CCUS, there have been a number of recent developments to climate strategy in the country.** In Egypt, a national monitoring, reporting, and verification framework has been developed, though significant funding gaps must be bridged before the system can be implemented. The country is investigating developing a carbon tax and emissions trading system, though neither have been implemented at the time of writing. The launch of the Egypt National Climate Change Strategy—2050, at the COP26 international climate summit, represents a significant development in Egypt's climate policy environment. |
| **Stakeholder engagement** | **Relevant stakeholders in Egypt are increasingly engaged to develop low-emissions technologies.** A memorandum of understanding concerning emissions reduction projects was signed between Egypt's National Gas Holding Company (EGAS) and Spain's industry and power sector construction firm, Técnicas Reunidas. Further, the African Development Bank has stated intent to increase general spending in Egypt's energy sector. Such engagements between government bodies and potential CCUS project developers in Egypt are required to facilitate large-scale deployment of CCUS in the country.[59] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; ETS = emissions trading system; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

57 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
58 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
59 Information obtained through engagement with consultancy involved in CCUS, hydrogen, and renewable energy projects in Egypt.

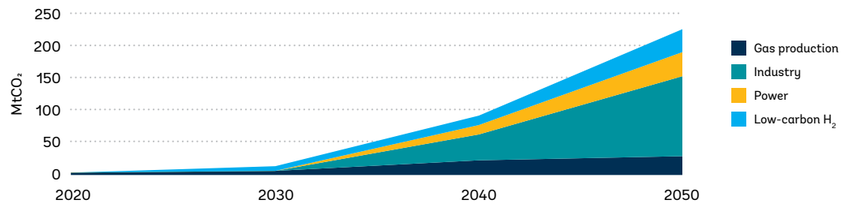
## 6.4 India

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in India is estimated in this study to have the potential to mitigate up to 7 percent of emissions forecast under a baseline scenario by 2050, with the greatest opportunity estimated to be in industry.** CCUS does not currently contribute to emissions reductions in India. This study finds gas CCUS in India could contribute 159 $MtCO_2$ in emissions reductions per year, by mid-century, in a 1.75°C scenario, or 7 percent of the roughly 2.4 $GtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. The greatest abatement opportunity emerges in industry, which accounts for around 57 percent of the total national opportunity by 2050. Low-carbon hydrogen production and use accounts for a further 32 percent of the national opportunity. By 2030, almost the entirety of the 23 $MtCO_2$ gas CCUS abatement potential is achievable in the relatively low-cost applications of gas production and ammonia and methanol production.<br><br>**Gas CCUS abatement opportunity in India, 1.75°C scenario**<br><br> |
| **Progress to date** | **India has experience in carbon capture and usage, but not dedicated storage.** Planned projects in India include low-carbon hydrogen production at the Indian Oil's Gujarat refinery, for applications in the transport sector, and feasibility studies investigating national EOR potential. No pilot or commercial CCS projects are currently operational. A $CO_2$ usage project was conducted by Carbon Clean Solutions in 2013, which found industrial uses for $CO_2$ captured at a natural gas combustion kiln. The project had a capacity of 7.7 $ktCO_2$/year. |
| **Storage readiness** | **Emissions in India are high, though estimated storage volumes are likely adequate to sequester them for over 50 years.** Emissions from industry, power generation, and heat totalled roughly 1.8 $GtCO_2$ in 2019. In 2008, an IEA project conducted a high-level estimation of storage potential in the Indian subcontinent and established emissions from the country's largest point sources. More recently, the Indian Institutes of Technology and Management have conducted detailed source-sink mapping for India's largest emitters. This study estimates storage potential in India to range from 100–700 $GtCO_2$, implying likely adequate storage potential to sequester present-day emissions for 55–390 years. |
| **Cost of capture** | **There are low-cost opportunities which can facilitate the near-term deployment of gas CCUS in India.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 0.7 $MtCO_2$ and 22 $MtCO_2$/year, respectively, in India by 2030. This represents almost the entirety of India's total gas CCUS abatement opportunity by 2030. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost applications represent roughly one-third of India's total gas CCUS abatement opportunity.<br><br>**Moderate- to high-cost opportunities could abate a further 107 $MtCO_2$/year by 2050 in India.** Further, moderate- to high-cost applications of gas CCUS in gas power generation and industry, could abate up to 107 $MtCO_2$/year by 2050, or 67 percent of the country's total gas CCUS abatement opportunity by mid-century. |
| **Infrastructure requirements—Dedicated storage** | **In India, a significant share of emissions captured from industry and power could be transported and stored with only a low infrastructure investment.** 25 percent of power generation emissions are generated within 100 km of potential storage sites, implying that roughly a quarter of emissions from the sector could be transported and stored with only a low infrastructure investment. In industry, 29 percent of emissions are generated within such proximity, implying similarly low infrastructure requirements.[60] |
| **EOR potential** | **In India, the proximity of power and industry emissions to potential EOR sites implies relatively high infrastructure requirements to generate revenues from storage activities.** India likely has significant opportunities to exploit EOR, with this study identifying roughly 1.4 $GtCO_2$ injection potential. In India, 8 percent of power generation emissions and 13 percent industry emissions are generated within 100 km of potential storage sites, requiring only a low infrastructure investment to generate revenues through storage activities.[61] |
| **Legal and regulatory environment** | **India does not currently regulate CCUS technology or activities.** It does not currently have any laws and regulations specific to governing CCUS technology or activities. As per the Global CCS Institute, India is categorized as "Band C," implying that there are also very few existing laws that are relevant across the CCS project cycle. |
| **Policy environment** | **India recently pledged to reach carbon neutrality by 2070, and CCUS research and development efforts are accelerating, though no private financing mechanism is yet in place.** At the COP26 international climate summit, India pledged to reach carbon neutrality by 2070. The government has been funding CCUS research and development and pilot projects, driven by the national Department for Science and Technology. Two national departments were admitted to the Cooperation for Accelerating CCUS Technologies in 2020. At the time of writing, no carbon tax or emissions trading system is in place. |
| **Stakeholder engagement** | **Stakeholder engagement over CCUS in India is relatively strong among both public and private actors.** Stakeholder interviews conducted for the present study suggest national research centres and industry stakeholders are driving the development of CCUS activities. Both public and private actors are reaching alignment over the need to deploy CCUS at scale to meet emissions targets. In its Second Biennial Update Report submitted in 2018, India identified that CCUS technologies could help in reducing emissions from the energy sector.[62] |

Source: World Bank, based on multiple sources.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

60 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
61 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
62 Information obtained through interviews with Indian universities engaged in CCUS research and development, including $CO_2$ storage characterization.

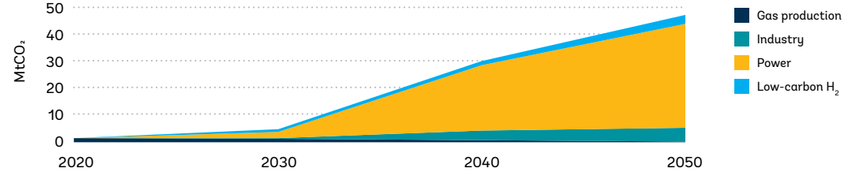
## 6.4 Indonesia

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Indonesia is estimated in this study to have the potential to mitigate up to 28 percent of emissions forecast under a baseline scenario by 2050, with the greatest opportunity estimated to be in industry.** CCUS does not currently contribute to emissions reductions. This study finds that gas CCUS in Indonesia could contribute 226 $MtCO_2$ of emissions reductions per year by mid-century in a 1.75°C scenario, or 28 percent of the 811 $MtCO_2$ expected to be emitted in 2050 under a baseline scenario. The greatest opportunity emerges in industry, which accounts for 124 $MtCO_2$, or 55 percent of the total national potential, by 2050. Important low- to moderate-cost opportunities also arise in natural gas production and gas power generation, worth 29 and 38 $MtCO_2$/year by 2050 respectively. CCUS with low-carbon hydrogen production and use could capture 35 $MtCO_2$/year by 2050, or 16 percent of the total abatement potential. By 2030, 84 percent of Indonesia's gas CCUS abatement potential is achievable at relatively low cost, which could help facilitate the near-term deployment of gas CCUS in the country.<br><br>**Gas CCUS abatement opportunity in Indonesia, 1.75°C scenario**<br><br> |
| **Progress to date** | **Plans are underway to develop CCUS projects in Indonesia in the near future, but none are currently operational.** PERTAMINA, operator of the Gundih Acid Gas Processing Plant, is collaborating with the ADB to deploy CCUS at its Enhanced Gas Recovery (EGR) gas production facility, with the potential to sequester 0.3 $MtCO_2$/year. BP has conducted an EGR study at the Tangguh Liquefied Natural Gas Plant, demonstrating a potential to sequester 30 $MtCO_2$ over 10 years, should CCUS be deployed at the facility. |
| **Technical suitability** | **Indonesia has adequate storage potential to store domestic emissions for many years. Emissions from industry, power generation, and heat totalled 407 $MtCO_2$ in 2019.** Storage characterization in Indonesia is nascent, with volume estimates uncertain. This study estimates total storage volumes in Indonesia to range from 200–1,400 $GtCO_2$, the large range reflecting the uncertainty of preliminary desk studies. The Bandung Institute of Technology is currently conducting further characterization of Indonesian storage sites, and ExxonMobil and PERTAMINA signed a memorandum of understanding in November 2021 to identify $CO_2$ storage sites. Based on this study's estimation of storage resources, Indonesia has adequate capacity to store current emissions from industry, power, and heat generation for over 500 years. |
| **Cost of capture** | **There are low-cost opportunities, which can facilitate the near-term deployment of gas CCUS in Indonesia.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 6.2 $MtCO_2$ and 5.1 $MtCO_2$/year respectively in Indonesia by 2030. This represents roughly 84 percent of Indonesia's total gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, low-cost opportunities represent roughly 18 percent of Indonesia's total gas CCUS abatement potential.<br><br>**Moderate- to high-cost opportunities could abate a further 185 $MtCO_2$/year, by 2050.** Further moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 185 $MtCO_2$/year by 2050, or 82 percent of the country's total gas CCUS abatement opportunity by mid-century. |
| **Infrastructure requirements—Dedicated storage** | **In Indonesia, roughly two thirds of emissions from industry and power could be stored with only a low infrastructure investment.** In Indonesia, 61 percent of power generation emissions are generated within 100 km of potential storage sites, implying nearly two thirds of emissions from the sector could be stored with only a low infrastructure investment. In industry, 69 percent of emissions are generated within such proximity, implying similarly low infrastructure requirements to transport and store captured $CO_2$, for over two thirds of emissions from the sector.[63] |
| **EOR potential** | **In Indonesia, over half of emissions from industry and power generation could generate revenues through EOR with only a low infrastructure investment.** Indonesia likely has significant opportunities to exploit EOR, with this study identifying roughly 1.3 $GtCO_2$ injection potential in the country. In Indonesia, 51 percent of power generation emissions and 61 percent industry emissions are generated within 100 km of potential EOR sites, implying over half of the emissions from these sectors could generate revenues through storage activities with only a low infrastructure investment.[64] |
| **Legal and regulatory environment** | **Though CCUS activities are currently unregulated in Indonesia, there is movement toward establishing legislation.** Currently, CCUS activities are governed under oil and gas industry regulation. CCUS-specific regulation is under draft, with support from the ADB. Growing governmental recognition of the role of CCUS in reaching climate targets is likely to spur greater regulatory development in the near term. |
| **Policy environment** | **Climate commitments in Indonesia are not supported by a funding mechanism to facilitate CCUS deployment. Indonesia's NDC requires a 29 percent reduction in emissions compared to a business-as-usual scenario by 2030.** Natural gas deployment is incentivized by the government's position not to commission new coal power plants as of May 2021. Further, at the COP26 international climate summit, Indonesia signed the Global Coal to Clean Power Transition Statement, which commits the country to phase out unabated coal power generation by the 2040s. Carbon pricing has not yet been implemented in the country. |
| **Stakeholder engagement** | **Stakeholder engagement over CCUS in Indonesia is strong.**[65] Stakeholder interviews conducted for this study suggest that project developers, investors, and the Indonesian government are currently well engaged to deliver the country's planned CCUS projects. In the near term, the Japanese government and PERTAMINA are in discussion to deliver CCUS at the Gundih Acid Gas Processing Plant. |

Source: World Bank, based on multiple sources.
Note: ADB = Asian Development Bank; CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EGR = enhanced gas recovery; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

63 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
64 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
65 Information obtained through engagement with a range of senior energy and CCUS specialists, including from the Asian Development Bank, the Indonesia Energy Program, and the Institut Teknologi Bandung.

## 6.6 Kazakhstan

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Kazakhstan is estimated in this study to have the potential to mitigate up to 21 percent of emissions forecast under a baseline scenario by 2050, with gas power generation estimated to account for the majority of this potential. CCUS does not currently contribute to emissions reductions.** This study finds gas CCUS could contribute 47 $MtCO_2$ of emissions reductions per year by mid-century in a 1.75°C scenario, or 21 percent of the 231 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. The vast majority of Kazakhstan's abatement potential emerges in CCUS with gas power generation, which captures 39 $MtCO_2$, or 87 percent of the total abatement opportunity, by 2050. Further opportunities exist in industry and gas production, accounting for roughly 9 percent of the abatement potential, collectively. The remainder of Kazakhstan's gas CCUS abatement opportunity lies in low-carbon hydrogen production and use, which could account for 3.4 $MtCO_2$/year by 2050. By 2030, roughly 37 percent of Kazakhstan's gas CCUS abatement opportunity emerges in the relatively low-cost applications of gas production and ammonia and methanol production, which could help facilitate the near-term deployment of gas CCUS in the country.<br><br>**Gas CCUS abatement opportunity in Kazakhstan, 1.75°C scenario**<br><br> |
| **Progress to date** | **There are no existing or planned CCUS projects in Kazakhstan to date.** It currently has no industry, power, or gas production CCUS projects planned, either pilot or commercial. |
| **Storage readiness** | **Kazakhstan likely has sufficient storage capacity to sequester domestic emissions.** Industry, power generation and heat emissions totalled 143 $MtCO_2$ in 2019. Research conducted by the Green Energy and Environmental Laboratory at Nazarbayev University estimated storage capacity in Kazakhstan at approximately 583 $GtCO_2$. The majority of this capacity exists within six basins, with the Precaspian basin determined to be the most suitable for geological $CO_2$ storage. This study estimates total $CO_2$ storage capacity at 280–1,990 $GtCO_2$ implying sufficient capacity to store current emissions for over 1,900 years. |
| **Cost of capture** | **There are low-cost opportunities which can facilitate the near-term deployment of gas CCUS in Kazakhstan.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 1.3 $MtCO_2$ and 0.5 $MtCO_2$/year respectively by 2030. This represents roughly 37 percent of Kazakhstan's total, near-term gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost applications represent roughly 3 percent of the country's total gas CCUS abatement opportunity.<br><br>**Moderate- to high-cost opportunities could abate a further 46 $MtCO_2$/year by 2050.** Further, moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 46 $MtCO_2$/year by 2050, or 97 percent of the country's total gas CCUS abatement opportunity by mid-century. |

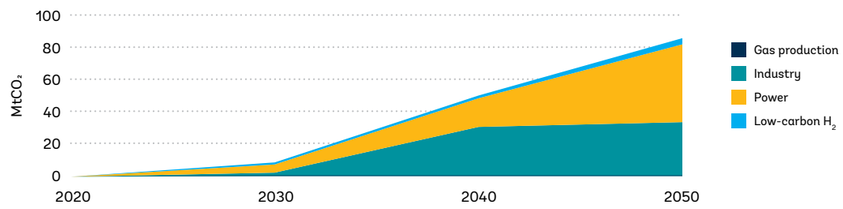


| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **In Kazakhstan, a significant quantity of $CO_2$ captured from power generation could be stored with only a low infrastructure investment.** 11 percent of power generation emissions are generated within 100 km of potential storage sites, implying these emissions could be stored with only a low infrastructure investment. In industry, no emissions currently are generated within such proximity.[66] |
| **EOR potential** | **In Kazakhstan, 11% of power generation emissions could generate revenues from storage activities with only a low infrastructure investment.** Kazakhstan likely has opportunities to exploit EOR, with this study identifying roughly 3.8 $GtCO_2$ injection potential in the country. The location of potential EOR sites mirrors that of storage resources, with 11 percent of power generation emissions and no industry emissions generated within 100 km of potential EOR sites. For these power generation emissions, only a low infrastructure investment would be required to generate revenues from $CO_2$ storage activities.[67] |
| **Legal and regulatory environment** | **Kazakhstan does not currently regulate CCUS activities.** No regulation specifically governing CCUS technology or activities currently exists. Further, no CCUS projects have been implemented under existing oil and gas industry regulation. |
| **Policy environment** | **Climate targets in Kazakhstan have previously focussed on the deployment of renewables, and the country recently announced a carbon neutrality target of 2060.** Kazakhstan's Environmental Code sets out a legal framework to support the implementation of the country's emissions trading system (launched in 2013), carbon budget, and carbon offset program. No specific policies exist to encourage the deployment of CCUS While Kazakhstan's NDC intends to meet its targets largely through deployment of renewable energy, the country's recently announced Doctrine for Carbon Neutrality of Kazakhstan by 2060 references a broad range of measures including gradual phase-out of coal power generation. |
| **Stakeholder engagement** | **Stakeholder engagement on CCUS in Kazakhstan is below that required to deploy the technology at scale in the country.** Stakeholder interviews conducted for the present study suggest government bodies in Kazakhstan are not sufficiently engaged with potential CCUS project developers to deploy CCUS at scale in the country.[68] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

66 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
67 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
68 Information obtained through consultation with stakeholders at the Green Energy & Environmental Research Group of Nazarbayev University, Astana, and a senior climate policy expert with in-depth knowledge of Kazakhstan's decarbonization strategy, working with environmental consultancy, Carbon Limits.

## 6.7 Mexico

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Mexico is estimated in this study to have the potential to mitigate up to 22 percent of emissions forecast under a baseline scenario by 2050, with significant opportunities estimated to emerge in both gas power generation and industry.** CCUS does not currently contribute to emissions reductions. This study finds gas CCUS in Mexico could contribute 86 $MtCO_2$ in emissions reductions per year by mid-century, in a 1.75°C scenario, or 22 percent of the 397 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. By 2050, CCUS with gas power generation could capture 48 $MtCO_2$, and industry CCUS, 33 $MtCO_2$/year—57 percent and 39 percent of the country's total abatement potential, respectively. Low-carbon hydrogen production i could capture roughly 4 $MtCO_2$/year by 2050 under the same scenario. By 2030, 9 percent of Mexico's gas CCUS abatement opportunity arises in the low-cost applications of gas production and ammonia and methanol production.<br><br>**Gas CCUS abatement opportunity in Mexico, 1.75°C scenario**<br><br> |
| **Progress to date** | **No CCUS projects are currently operational in Mexico, though pilot projects have previously been planned.** PEMEX have investigated deploying CCUS at their Cosoleacaque petrochemical facility, reinjecting captured $CO_2$ at the nearby Brilliante field, to exploit EOR. Work is also underway investigating opportunities to develop pilot $CO_2$ capture projects in the cement and iron and steel sectors, with support from the World Bank. |
| **Technical suitability** | **Mexico likely has adequate capacity to support the storage of current emissions for many years. It generated 251 $MtCO_2$ in 2019, from industry, heat, and power generation.** Two high-level estimations of storage potential have been conducted: The North American Carbon Storage Atlas and Mexico's Geological $CO_2$ Storage Atlas. These studies are yet to be supported by detailed wellhead analysis, leading to large uncertainty in the estimated range of total storage volumes. This study estimates storage volumes to range from 130 to 900 $GtCO_2$, implying likely adequate capacity to store Mexico's industry, power generation, and heat emissions for over 500 years. |
| **Cost of capture** | **There are low-cost opportunities which can help facilitate the near-term deployment of gas CCUS in Mexico.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could each account for 0.4 $MtCO_2$/year by 2030. This represents roughly 9 percent of Mexico's total, near-term gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost opportunities represent less than 1 percent of the total gas CCUS abatement potential.<br><br>**Moderate- to high-cost opportunities could abate a further 85 $MtCO_2$/year by 2050.** Further, moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 85 $MtCO_2$/year by 2050, or >99 percent of the country's total gas CCUS abatement opportunity by mid-century. |

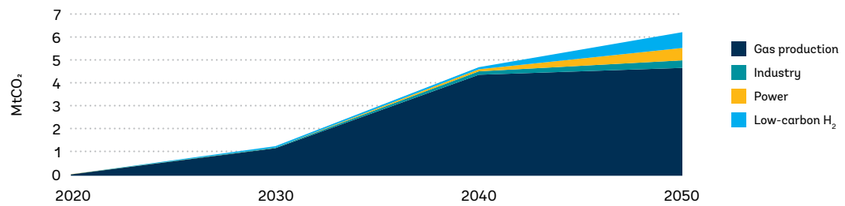


| Factor | Performance |
|---|---|
| **Infrastructure requirements—Dedicated storage** | **In Mexico, significant quantities of $CO_2$ captured from power generation and industry could be stored with only a low infrastructure investment.** 42 percent of power generation emissions and 39 percent of industry emissions are generated within 100 km of potential storage sites. This significant share of emissions could be transported and stored with only a low infrastructure investment.[69] |
| **EOR potential** | **There are opportunities to exploit EOR in industry and power with only a low infrastructure investment.** Mexico likely has significant opportunities to exploit EOR, with this study identifying roughly 5.2 $GtCO_2$ injection potential in the country. 9 percent of power and 4 percent of industry emissions are generated within 100 km of potential EOR sites, implying these emissions could be used to generate revenues through storage activities, with only a low infrastructure investment.[70] |
| **Legal and regulatory environment** | **Mexico does not yet regulate CCUS activity but is engaged with key international organizations to address this.** Although Mexico does not currently regulate CCUS activities, the country is an observing member of the ISO/TC 265 committee, developing international standards to govern CCUS activities. The World Bank is also providing support for the development of regulatory frameworks for CCUS in the country. |
| **Policy environment** | **Policy foundations to support CCUS deployment are present.** The Mexican government recognizes CCUS as a tool to reach the targets of their NDCs, reducing emissions by 22 percent compared to a business-as-usual scenario by 2030. No specific deployment targets have been identified. A carbon tax priced at $2/$tCO_2$ provides the basis of a funding mechanism for future projects, though prices at the time of writing are too low to incentivize the at-scale deployment of CCUS. |
| **Stakeholder engagement** | **Industry and government stakeholders are currently limited in their alignment to deliver CCUS projects at scale in Mexico.** Stakeholder interviews and targeted literature reviews conducted for the present study find two CCUS working groups have been formed by previous administration, with the aim of aligning industry and public sector stakeholders to deliver CCUS. However, both groups were dissolved at the time of writing.[71] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

69 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
70 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
71 Information obtained through consultation with key stakeholders at the University of Edinburgh's Carbon Capture Research department and the National Autonomous University of Mexico's Mexican Platform for Capture and Storage of $CO_2$ MeCCS.

## 6.8 Mozambique

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Mozambique is estimated in this study to have the potential to mitigate up to 34 percent of emissions forecast under a baseline scenario by 2050, with the majority of the abatement potential estimated to arise in natural gas production.** CCUS does not currently contribute to emissions reductions. This study finds gas CCUS could contribute 6.2 $MtCO_2$ in emissions reductions per year by mid-century in a 1.75°C scenario, or 34 percent of the 18 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. CCUS with natural gas production accounts for 4.7 $MtCO_2$, or 75 percent of the total national abatement potential by 2050. More limited opportunities also emerge in industry and power generation, accounting for 5 percent and 9 percent of the total national abatement potential respectively. By 2030, 95 percent of Mozambique's gas CCUS abatement opportunity lies in low-cost CCUS with gas production, which could help facilitate the near-term deployment of gas CCUS in the country.<br><br>**Gas CCUS abatement opportunity in Mozambique, 1.75°C scenario**<br><br> |
| **Progress to date** | **There are no existing or planned CCUS projects in Mozambique to date.** No pilot or commercial CCUS activities are currently established or under planning or development. |
| **Technical suitability** | **Mozambique likely has sufficient storage capacity to store domestic emissions for the foreseeable future.** Emissions from industry, power generation, and heat totalled 3 $MtCO_2$ in 2019. In 2014, Norwegian registrar Det Norske Veritas (DNV) estimated storage potential of the Mozambique basin at 2.3–230 $GtCO_2$. Another 2014 study estimated a further 0.2–0.4 $GtCO_2$ storage capacity in the Rovuma basin. This study estimates overall storage capacity at 60–430 $GtCO_2$, implying likely sufficient capacity to store domestic emissions for the foreseeable future. |
| **Cost of capture** | **There are low-cost opportunities which can facilitate the near-term deployment of gas CCUS in Mozambique.** Low-cost CCUS applications ($15/$tCO_2$) in gas production could account for 1.2 $MtCO_2$/year in Mozambique, by 2030. This represents roughly 95 percent of Mozambique's total, near-term gas CCUS abatement opportunity. These low-cost opportunities could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost opportunities represent roughly 75 percent of the yearly gas CCUS abatement potential.<br><br>Moderate- to high-cost opportunities could abate a further 2 $MtCO_2$/year by 2050. Further moderate- to high-cost applications of gas CCUS in gas power generation and industry, could abate up to 2 $MtCO_2$/year by 2050, or roughly 25 percent of the country's total gas CCUS abatement opportunity by mid-century. |

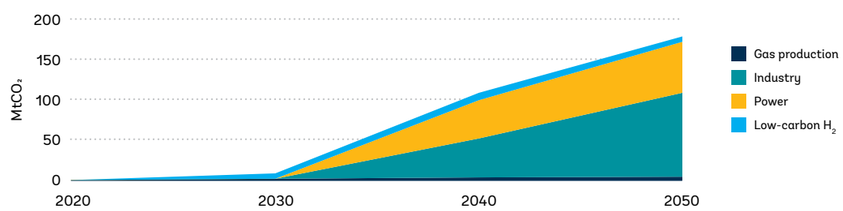


| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **In Mozambique, the vast majority of the country's gas CCUS abatement opportunity implies only low infrastructure requirements to store captured $CO_2$.** Infrastructure requirements are minimal for CCUS with gas production, which accounts for 75 percent of the gas CCUS abatement opportunity.[72] Beyond this, 2 percent of power generation emissions and no identified industry emissions are generated within 100 km of potential storage sites, with these emissions implying similarly low infrastructure requirements for storage.[73] |
| **EOR potential** | **Rystad Energy does not identify any fields with EOR injection potential in Mozambique.** As such, currently no industry or power emissions are generated within 100 km of potential EOR sites. This study notes that such opportunities may emerge in future, should EOR-suitable fields be developed.[74] |
| **Legal and regulatory environment** | **Mozambique does not currently regulate CCUS activities.** No regulations are established to govern CCUS activities, and there are no examples of projects being governed by existing oil and gas industry regulation. |
| **Policy environment** | **CCUS-relevant policies and public or private financing mechanisms in Mozambique are limited.** Climate action is supported through the Clean Development Mechanism of the Kyoto Protocol. Through its Intended NDC, Mozambique aims to reduce emissions by a cumulative total of 76.5 $MtCO_2$ over the period to 2030. Mozambique updated its NDC in December 2021 and is expected to submit a Biennial Update Report in 2022. The absolute emissions reductions targeted in the updated NDC represent a 75 percent reduction, relative to a business-as-usual scenario, by 2025. There is no national carbon pricing system or carbon tax. |
| **Stakeholder engagement** | **Stakeholder alignment to deliver CCUS projects in Mozambique is limited.** Stakeholder interviews conducted by the presented study suggest there is currently no alignment between relevant government bodies such as the Ministry of Land, Environment and Rural Development and oil and gas industry stakeholders such as the National Hydrocarbon Company (ENH), to deliver CCUS projects.[75] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; NDC = Nationally Determined Contribution; $MtCO_2$ = million tons of carbon dioxide.

72 In Mozambique, 75 percent of the modelled gas CCUS abatement potential emerges in CCUS with gas production. While not quantitatively assessed within the study framework, storage opportunities in gas production likely imply low infrastructure requirements, as $CO_2$ separation typically occurs at, or in close proximity to, potential reinjection sites.
73 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
74 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
75 Information obtained through consultation with a senior researcher at Eduardo Mondlane University, and advisor to the Energy Research Centre in Mozambique (Centros de Pesquisa em Engenharia), with expertise in CCS, ETS, and energy transition policy.

## 6.8 Saudi Arabia

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Saudi Arabia is estimated in this study to have the potential to mitigate up to 31 percent of emissions forecast under a baseline scenario by 2050, with significant opportunities estimated to emerge in industry and gas power generation.** CCUS at the Uthmaniyah $CO_2$-EOR project currently captures roughly 0.8 $MtCO_2$/year, or <1 percent of emissions in the country. This study finds gas CCUS in Saudi Arabia could contribute 180 $MtCO_2$ of emissions reductions per year by mid-century in a 1.75°C scenario, or 31 percent of the 581 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. CCUS with industrial gas use accounts for 58 percent of the total national abatement potential by 2050, CCUS with gas power generation 35 percent, and CCUS with natural gas production roughly 3 percent. CCUS with low-carbon hydrogen production and use could abate roughly 7 $MtCO_2$/year under the same scenario. There exist significant low-cost opportunities by 2030, which could help facilitate the near-term deployment of gas CCUS.<br><br>**Gas CCUS abatement opportunity in Saudi Arabia, 1.75°C scenario**<br><br> |
| **Progress to date** | **Saudi Arabia has experience in both carbon utilization and storage.** It currently has two operational CCUS projects. The Uthmaniyah $CO_2$-EOR project operated by Saudi Aramco has been capturing 0.8 $MtCO_2$/year since 2015, sequestering it underground during enhanced oil recovery. The Jubail $CO_2$ capture and utilization facility operated by SABIC captures 1.5 $KtCO_2$/day, repurposing the carbon in methanol, urea, oxy-alcohol, and polycarbonate production. |
| **Technical suitability** | **Saudi Arabia likely has sufficient storage capacity to sequester domestic emissions for over 400 years.** Industry, power generation, and heat emissions totalled 354 $MtCO_2$ in 2019. Saudi Arabia conducted high-level studies of storage capacity, identifying sufficient storage resources to sequester 25 $GtCO_2$ with EOR activities. The Global CCS Institute estimates storage potential in Saudi Arabia's oil and gas fields at 5 $GtCO_2$. Further, the Oil and Gas Climate Initiative highlights that Saudi Arabia has sufficient storage resources to offer storage services to neighbouring countries. Rystad Energy estimates storage capacity to range from 140 to 1,000 $GtCO_2$, implying likely sufficient resources to store current domestic emissions for over 400 years. |
| **Cost of capture** | **There are low-cost opportunities which can help facilitate the near-term deployment of gas CCUS in Saudi Arabia.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 2.5 $MtCO_2$ and 5.1 $MtCO_2$/year respectively by 2030. This represents 81 percent of total, near-term gas CCUS abatement opportunity. These low-cost applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost opportunities represent roughly 5 percent of Saudi Arabia's total gas CCUS abatement opportunity.<br><br>**Moderate- to high-cost opportunities could abate a further 172 $MtCO_2$/year by 2050, in Saudi Arabia.** Further moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 172 $MtCO_2$/year by 2050, or 95 percent of the country's total gas CCUS abatement opportunity by mid-century. |



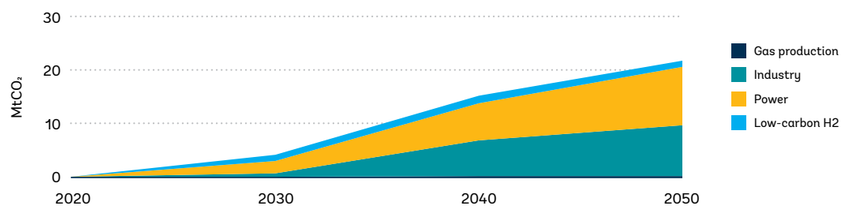
| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **In Saudi Arabia, storing the majority of industry and power emissions would require only a low infrastructure investment.** 73 percent of power generation emissions are generated within 100km of potential storage sites, implying low infrastructure requirements to store nearly three quarters of emissions from the sector. In industry, 53 percent of emissions are generated within such proximity of potential storage sites, implying similar infrastructure requirements.[76] |
| **EOR potential** | **A significant quantity of industry and power emissions could be used to exploit EOR with only a low infrastructure investment.** Saudi Arabia likely has significant opportunities to exploit EOR, with Rystad Energy identifying roughly 40 $GtCO_2$ injection potential in the country. 65 percent of power generation emissions and 35 percent of industry emissions are generated within 100 km of potential EOR sites, implying only a low infrastructure investment would be required for these emissions to generate revenues through storage activities.[77] |
| **Legal and regulatory environment** | **Saudi Arabia has no regulatory framework specifically governing CCUS activities.** CCUS projects are largely state-operated, easing potential monitoring and liability issues. Saudi Aramco is currently developing a $CO_2$-EOR project, which will see capture and transport activities governed by oil and gas industry regulation. |
| **Policy environment** | **Public funding for CCUS in Saudi Arabia is strong, and emissions reduction targets were increased in the country's recent NDC update.** Saudi Arabia provides significant public financing for CCUS projects, establishing both pilot and commercial operations. At the time of writing, updated NDC pledges to reduce greenhouse gas emissions by 278 $MtCO_2e$ by 2030—more than twice what the country had previously committed to. No carbon pricing or carbon tax system yet exists. |
| **Stakeholder engagement** | **Stakeholders are clearly aligned to deliver CCUS projects in Saudi Arabia.** Stakeholder consultations conducted for the present study suggest state ownership of CCUS-relevant companies and organizations typically allows projects to be delivered smoothly. Actors such as the Ministry of Energy (regulatory body), Saudi Aramco (National Oil Company), and the General Electric Corporation (national energy provider) are coordinated in developing and implementing CCUS infrastructure in line with national objectives.[78] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; NDC = Nationally Determined Contribution; $MtCO_2$ = million tons of carbon dioxide.

76 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
77 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
78 Information obtained through consultation with stakeholders at the King Abdullah City for Atomic & Renewable Energy.

## 6.10 Ukraine

The country analysis of Ukraine was undertaken prior to the Russian invasion and therefore may change significantly from what is presented here.

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Ukraine is estimated in this study to have the potential to mitigate up to 11 percent of emissions forecast under a baseline scenario by 2050, with the majority of abatement potential estimated to emerge in gas power generation and industry.** CCUS does not currently contribute to emissions reductions. This study finds gas CCUS could contribute 22 $MtCO_2$ in emissions reductions per year, by mid-century, in a 1.75°C scenario, or 11 percent of the 197 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. The majority of this potential exists in CCUS with gas power generation, which accounts for 11 $MtCO_2$/year by 2050, or 50 percent of the total national abatement opportunity. Further opportunities emerge in industry and gas production, worth 9 $MtCO_2$ and 0.4 $MtCO_2$/year by 2050, respectively. Low-carbon hydrogen production and use could account for 1 $MtCO_2$/year by 2050, under the same scenario. There exist significant low-cost opportunities which could help facilitate the near-term deployment of gas CCUS.<br><br>**Gas CCUS abatement opportunity in Ukraine, 1.75°C scenario**<br><br> |
| **Progress to date** | **No CCUS projects exist in Ukraine but there are plans to deliver projects this decade.** While there are no CCUS-related projects currently, DTEK Oil & Gas plans to develop CCUS at the Semyrenskivske conventional offshore gas field from 2024. |
| **Technical suitability** | **Ukraine likely has access to adequate geological storage resources to store domestic emissions for over 420 years.** Emissions from power generation, industry, and heat totalled 118 $MtCO_2$, in 2019. Several high-level assessments of storage potential have been conducted in Ukraine (Bellona, LCOIR-UA), though the results of these desktop assessments are yet to be substantiated by wellhead data. The studies suggest limited depleted field volume but highlight significant saline formations with potential to store substantial volumes of $CO_2$. Rystad Energy estimates $CO_2$ storage resources to range from 50 to 400 $GtCO_2$, implying likely adequate capacity to store current emissions for over 420 years. |
| **Cost of capture** | **There are low-cost opportunities, which can help facilitate the near-term deployment of gas CCUS in Ukraine.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production could account for roughly 1 $MtCO_2$/year by 2030. This represents roughly 24 percent of Ukraine's total, near-term gas CCUS abatement opportunity, and as such, these applications could help facilitate the near-term deployment of gas CCUS in the country. By 2050, such low-cost opportunities represent roughly 4 percent of total yearly gas CCUS abatement potential.<br><br>**Moderate- to high-cost opportunities could abate a further 21 $MtCO_2$/year by 2050.** Further moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 21 $MtCO_2$/year by 2050, or 96 percent of the country's total gas CCUS abatement opportunity by mid-century. |

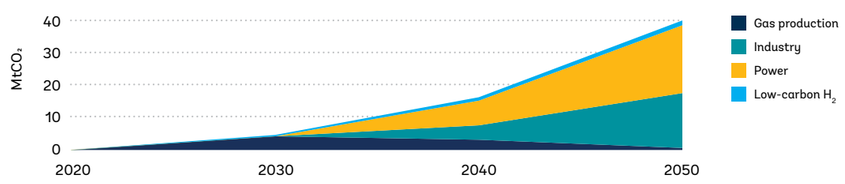


| Factor | Performance |
|---|---|
| **Infrastructure requirements—dedicated storage** | **In Ukraine, the infrastructure requirements to store captured $CO_2$ are likely to be low in both power generation and industry.** 66 percent of power generation emissions and 85 percent of industry emissions are generated within such proximity of potential storage sites, implying low infrastructure requirements, on average.[79] |
| **EOR potential** | **There are opportunities to exploit EOR with industry and power emissions with only a low infrastructure investment.** Ukraine likely has opportunities to exploit EOR, with Rystad Energy identifying roughly 0.6 $GtCO_2$ of injection potential in the country. In Ukraine, 15 percent of power generation emissions and 5 percent of industry emissions are generated within 100 km of potential EOR sites, implying only a low infrastructure investment is required for these emissions to generate revenues through storage activities.[80] |
| **Legal and regulatory environment** | **CCUS technology and activities are not currently regulated.** Ukraine does not have any CCUS-specific laws to govern the CCUS project life cycle, and there are no such laws currently under development. |
| **Policy environment** | **Ukraine's climate commitments include a target for carbon neutrality by 2060.** Ukraine has committed to achieving carbon neutrality by 2060 in its National Economic Strategy to 2030. Further, the country's NDC commits to reducing emissions to 60 percent of 1990 levels by 2030. A carbon tax covering 70 percent of industry and power emissions provides a basis for private finance for low-carbon technologies, though prices at the time of writing are likely too low to effectively incentivize investment in CCUS. |
| **Stakeholder engagement** | **Stakeholder engagement to promote gas CCUS in Ukraine is limited, at the time of writing.** Stakeholder interviews conducted for the present study suggest key stakeholders, such as DTEK Oil & Gas, the Ministry of Energy and Coal, and the Ministry of Ecology and Natural Resources, are limited in their alignment to deliver gas CCUS at scale in the country.[81] |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

79 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
80 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.
81 Information obtained through consultation with stakeholders at the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine, and the Centre of Environment and Development.

## 6.11 Vietnam

| Factor | Performance |
|---|---|
| **Overall opportunity** | **Gas CCUS in Vietnam is estimated in this study to have the potential to mitigate up to 12 percent of emissions under a baseline scenario by 2050, with significant opportunities estimated to emerge in industry and gas power generation.** CCUS does not currently contribute to emissions reductions. This study finds gas CCUS could contribute 40 $MtCO_2$ of emissions reductions per year by mid-century in a 1.75°C scenario, or 12 percent of the 324 $MtCO_2$ anticipated to be emitted in 2050 under a baseline scenario. CCUS with gas power generation accounts for 21 $MtCO_2$ and industry 17 $MtCO_2$/year by 2050, or 52 percent and 43 percent of the total national abatement potential, respectively. Low-carbon hydrogen production could abate up to 1.6 $MtCO_2$/year by 2050. By 2030, almost the entirety of Vietnam's gas CCUS abatement potential (4.5 $MtCO_2$) is achievable in the low-cost applications of gas production and ammonia and methanol production, which could help facilitate the near-term deployment of gas CCUS in the country. These low-cost opportunities also extend to 2040.<br><br>**Gas CCUS abatement opportunity in Vietnam, 1.75°C scenario**<br><br> |
| **Progress to date** | **There are no existing or planned CCUS projects in Vietnam to date.** No pilot or commercial CCUS activities are currently established or under planning or development. |
| **Technical suitability** | **Vietnam likely has sufficient storage resources to store domestic emissions for over 100 years. Emissions from industry,** power generation, and heat totalled 227 $MtCO_2$ in 2019. The Asian Development Bank and Global CCS Institute jointly conducted a detailed assessment of storage capacity in 2013, estimating total storage resources at 12 $GtCO_2$. The IEA identified significant storage opportunities in the Southeast Asia region, which could be available for Vietnam to access. Rystad Energy estimates total storage volumes in the country at 25–180 $GtCO_2$, implying likely adequate capacity to store current domestic emissions for over 110 years. |
| **Cost of capture** | **There are low-cost opportunities which can facilitate the near-term deployment of gas CCUS in Vietnam.** Low-cost CCUS applications ($15–35/$tCO_2$) in gas production and ammonia and methanol production could account for 4.1 $MtCO_2$ and 0.4 $MtCO_2$/year respectively by 2030. This represents 99 percent of Vietnam's total near-term gas CCUS abatement opportunity. These low-cost opportunities also extend to 2040. By mid-century, roughly 5 percent of Vietnam's gas CCUS abatement opportunity emerges in such low-cost applications.<br><br>**Moderate- to high-cost opportunities could abate a further 38 $MtCO_2$/year by 2050.** Further moderate- to high-cost applications of gas CCUS in low-carbon hydrogen, gas power generation, and industry, could abate up to 38 $MtCO_2$/year by 2050, or 95 percent of the country's total gas CCUS abatement opportunity by mid-century. |



| Factor | Performance |
|---|---|
| **Infrastructure requirements—Dedicated storage** | **In Vietnam, the majority of emissions from industry and power generation could be stored with only a low infrastructure investment.** 87 percent of power generation emissions and 52 percent of industry emissions are generated within 100 km of potential storage sites, implying only a low infrastructure investment would be required to store these emissions.[82] |
| **EOR potential** | **There are opportunities to exploit EOR with emissions from power and industry with only a low infrastructure investment.** Vietnam likely has opportunities to exploit EOR, with Rystad Energy identifying roughly 0.5 $GtCO_2$ injection potential in the country. 32 percent of power generation emissions and 17 percent of industry emissions are generated within 100 km of potential EOR sites, implying only a low infrastructure investment would be required for these emissions to generate revenues through storage activities.[83] |
| **Legal and regulatory environment** | **Vietnam does not currently regulate CCUS activities.** As no CCUS projects have been developed no regulations are established to govern CCUS activities, and there are no examples of projects being governed by existing oil and gas industry regulation. |
| **Policy environment** | **Climate targets and relevant policy incentives are under development, and a net zero target of 2050 was recently announced.** The Vietnamese government is working together with the World Bank Partnership for Market Readiness to develop climate plans for the industry, power, and waste sectors. The plans are set to establish a greenhouse gas registry; monitoring, reporting, and verifications framework; and roadmap for market-based carbon pricing in the country. Vietnam has recently revized regulation to facilitate the development of an emissions trading system. Vietnam announced a net zero by 2050 target at the COP26 international climate summit, further details of which are yet to emerge at the time of writing. |
| **Stakeholder engagement** | **Stakeholder alignment to deliver CCUS projects in Vietnam is limited.** Recently, the Ministry of Industry and Trade joined the Asia CCUS network, launched in 2021. Beyond this, stakeholder consultations conducted by the present study suggest there is currently limited alignment between relevant government bodies and oil and gas industry stakeholders, to deliver CCUS projects. |

Source: World Bank, based on multiple sources.
Note: CCUS = carbon capture, utilization, and storage; $CO_2$ = carbon dioxide; EOR = enhanced oil recovery; $GtCO_2$ = gigatons of carbon dioxide; H2 = hydrogen; km = kilometer; $MtCO_2$ = million tons of carbon dioxide.

82 In the assessment framework developed for this study, if >66 percent of emissions are generated within 100 km of a potential storage site, infrastructure requirements are deemed to be low; >33 percent, moderate; and <33 percent, high.
83 EOR infrastructure requirements are assessed similarly to dedicated storage infrastructure requirements.

# Technical annex: modeling methodology

To accurately assess the role and value of gas CCUS, the report develops plausible and realistic energy scenarios, integrating a whole energy system model with a detailed electricity system model. The whole energy system model was undertaken in partnership with Imperial College London using the Grantham Institute's Times Integrated Assessment Model (TIAM-Grantham). TIAM-Grantham is a multiregion, least-cost optimizing model of the world energy system, generating decarbonization pathways in the power generation, transport, buildings, and industry sectors. The full energy sector analysis is complemented by detailed electricity system modeling using Imperial College's Whole-energy System Investment Model (WeSIM). This model includes a detailed characterization of electricity system resources and models reliability needs in detail. Finally, the two modeling approaches are integrated to develop detailed climate scenarios, which assessed the role and value of gas CCUS across sectors.

The carbon budget is imposed at the global level. Therefore, each region's decarbonization pathway in the short run is driven largely by NDCs and, in the long run, largely by that region's cost-effective contribution to meeting the global carbon budget.

Cost reductions in battery technology, along with cost reductions in renewable energy, CCUS, etc. were taken into account in the analysis. The modelling in this study covers the time horizon 2020-2100 (though with a focus on the period to 2050). On average, historical gas prices have deviated around 30% from their average levels based on BP Statistical Review of World Energy.

While political instability leads to much larger swings in prices, these tend to be short-lived and do not typically persist for several decades. This annex sets out the approach used in this study, in three sections:

- Section 1 describes the energy system modeling used to identify the overall role of gas CCUS at the global and regional levels.
- Section 2 describes the electricity system modeling used to identify the role of gas CCUS in power generation, at the global and regional levels.
- Section 3 describes how the national gas opportunity was estimated for the 11 case study countries covered in this report.

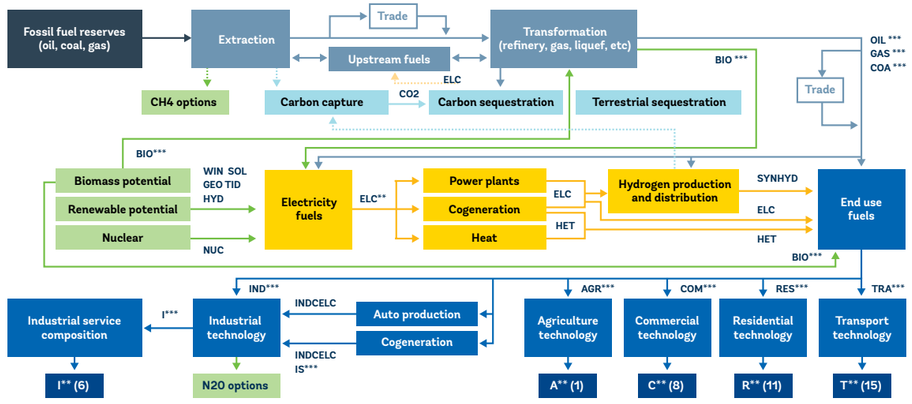
## Section 1: Energy system modeling

The whole energy system model was undertaken in partnership with Imperial College London using the TIAM-Grantham model. TIAM-Grantham is a multiregion, least-cost optimizing model of the world energy system, generating decarbonization pathways in the power generation, transport, buildings, and industry sectors (Box A1).



## Box A1. The TIAM-Grantham model

The TIAM-Grantham model[1] is a global, least-cost optimization model of the whole energy system. The figure below provides an overview of the whole energy system as it is modelled in TIAM-Grantham. The model captures the whole energy chain from extraction of fossil fuels from reserves through to usage of energy in the demand sectors. There are five demand sectors: agriculture, commercial buildings, residential buildings, transport, and industry. Within each of these demand sectors, energy demand is broken down into demand for different energy services such as heating and lighting in the residential sector, kilometes of transport in the transport sector, or tons of steel in industry. These can be supplied by different technologies, which in turn consume different fuels (e.g., coal, gas, biomass, and electricity).




The model is divided into 15 regions (a full list of the regions is provided Table A 1) and allows for trade of both fuel and carbon permits between regions. The starting input for the model is the high-level "storylines" of how the world is expected to develop in the future, that is, projections of GDP, population, economic structure, and households. These "drivers" are used to determine future demand for energy services such as lighting, kilometres of vehicle transport, heating, and tons of steel depending on an elasticity of demand according to the general formula:

$$\text{Demand} = \text{Driver}^{\text{Elasticity}}$$

In addition to the demand projections, the model requires the following additional inputs:

- Existing stock of current technologies in the starting ("Base") year must be specified in full for each region;
- Characteristics and costs of future technologies which can supply these demands; and
- Present and future sources of primary energy supply and their potentials/reserve capacity.

Using these inputs, the model can choose between different technology options to meet the given energy service demand. The objective function of the model is to minimize the total discounted energy system cost over the time horizon subject to a given climate constraint (e.g., a constraint on the $CO_2$ emissions or an exogenous carbon price).

[1] TIAM stands for TIMES Integrated Assessment Model and is based on the TIMES (The Integrated MARKAL-EFOM System) modeling platform.

Source: Grantham Institute: https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/collaborative-publications/Expect-the-Unexpected_CTI_Imperial.pdf.
Note: $CH_4$ = methane; $CO_2$ = carbon dioxide; $N_2O$ = nitrous oxide.



**Table A 1. TIAM region**

| TIAM code | Region name | Countries included |
|---|---|---|
| **AFR** | Africa | Algeria, Angola, Benin, Botswana, Cameroon, Republic of Congo, Democratic Republic of Congo, Côte d'Ivoire, Arab Republic of Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, Tanzania, Togo, Tunisia, Zambia, Zimbabwe, and Other Africa. |
| **AUS** | Australia | New Zealand, Oceanía Australia, New-Zealand, and Oceanía |
| **CAN** | Canada | Canada |
| **CHI** | China | China |
| **CSA** | Central & South America | Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, República Bolivariana de Venezuela, and Other Latin America. |
| **EEU** | Eastern Europe | Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Montenegro, Poland, Romania, Serbia (Kosovo), Slovenia, and Slovak Republic. |
| **FSU** | Former Soviet Union | Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyz Republic, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. |
| **IND** | India | India |
| **JPN** | Japan | Japan |
| **MEA** | Middle East | Bahrain, Cyprus, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, and Turkey. |
| **MEX** | Mexico | Mexico |
| **ODA** | Other Developing Asia | Bangladesh, Brunei Darussalam, Cambodia, Chinese Taipei, Indonesia, Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam, and Other Asia |
| **SKO** | Republic of Korea | Republic of Korea |
| **USA** | United States | United States |
| **WEU** | Western Europe | Austria, Belgium, Cyprus, Switzerland, Germany, Denmark, Finland, France, Greece, Ireland, Iceland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom |

Source: Original compilation using the Imperial College TIAM-Grantham model.

Scenarios were modelled for two temperature outcomes: a central scenario that achieves a 1.75°C temperature outcome in 2100, and a high ambition scenario that achieves a 1.5°C temperature outcome. In line with the IPCC Special Report on 1.5 Degrees, the 1.75°C and 1.5°C scenarios were defined by carbon budgets of 1,040 and 580 $GtCO_2$ budget levels, respectively, reflecting a 50 percent likelihood of achieving these temperature outcomes.[84] A cap on biomass of 125 EJ/year was applied in all scenarios.

In addition, the model constrained individual counties and regions based on all legal emissions limits. In 2030, this means hitting NDC emissions targets in 2030 as they are currently agreed with the UNFCCC. In 2050, this includes all legislated net zero emissions targets.

Where possible, technology cost and performance assumptions were aligned with published analysis by the International Energy Agency. The scenarios modelled are shown in Table A 2.

84 The IPCC's sixth assessment report published in 2021 estimates similar carbon budgets, confirming that the values used in this study remain in line with the latest climate science. In the analysis, the carbon budget is imposed at the global level. Each region's long-term decarbonization pathway and cumulative $CO_2$ emissions reflect that region's cost-effective contribution to meeting the global carbon budget.

**Table A 2. Scenarios modelled in this study**

| Scenario | Name | Climate objective | Description |
|---|---|---|---|
| 1 | Business as usual | None | Current policy scenario with no climate objective |
| 2 | Central | 1.75°C | Central scenario for this study |
| 3 | High gas price | 1.75°C | As Central but with high gas prices |
| 4 | Low gas price | 1.75°C | As Central but with low gas prices |
| 5 | No gas CCUS | 1.75°C | As Central but with gas CCUS disabled |
| 6 | 10-year delay | 1.75°C | As Central but with deployment of gas CCUS delayed by 10 years |
| 7 | 1.5°C | 1.5°C | 1.5°C |

Source: Original compilation.
Note: CCUS = carbon capture, utilization, and storage.

## Section 2: Power system modeling

The need for gas CCUS in a decarbonized electricity system will be is determined by the hour-by-hour variation in electricity demand, output of variable renewables, and the relationship between the two. Detailed electricity system modelling is needed to adequately characterize the role of gas CCUS at such temporal resolution.

The model used in this study is Imperial College's Whole-energy System Investment Model (WeSIM). This is an electricity system optimization model that estimates the least-cost investment and operation of electricity system resources needed to achieve a carbon target while maintaining reliable electricity supply. WeSIM has been widely used to investigate the future of the electricity system, with a focus on power sector decarbonization. Key features of WeSIM include:

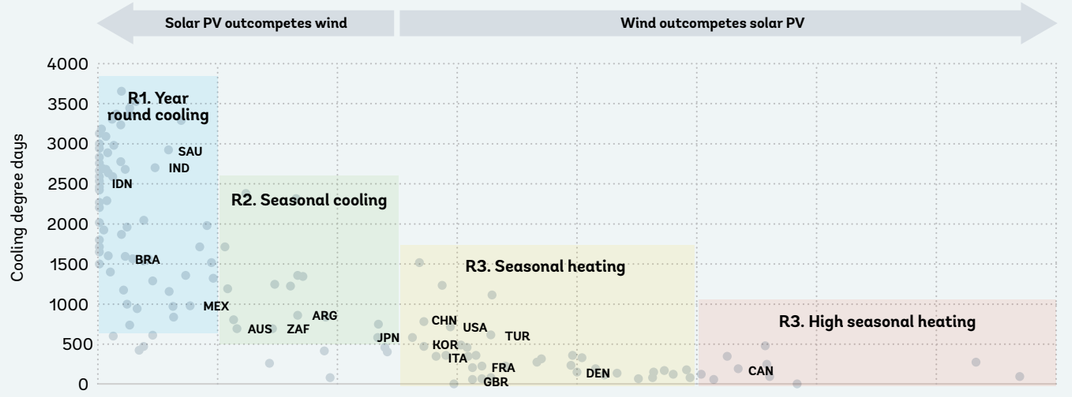
- Detailed characterization of all relevant electricity system resources. WeSIM models generation, network, storage, demand response, and interconnection resources.
- Detailed characterization of electricity system reliability. Specifically, WeSIM models scenarios that account for adequacy (ensuring that supply and demand are balanced at all times of the year), inertia (ensuring that there are sufficient turbine-based plants on the system to reduce sudden deviations in the frequency of the electricity system), and frequency response (ensuring that there is sufficient spare generation capacity to increase frequency in the event of a deviation).
- Accurate modeling of important electricity system characteristics. WeSIM accurately represents power flow limits, dynamic characteristics of generation plants, and operational constraints of storage and demand response.

To characterize the role of gas CCUS in the future generation mix across the 15 major countries and wider regions considered in this study, this study modeled four archetypal electricity systems that span the range of output of variable renewables and the variation in electricity demand that are expected to determine the role and value of CCUS. These archetypal electricity systems are shown in Figure A1, and described below:

- R1: year-round cooling. This archetype represents equatorial or tropical regions with minimal demand for space heating, and high demand for cooling with little seasonal variation. R1 regions are also characterized by high solar PV capacity factors. R1 regions include Indonesia and Brazil.
- R2: seasonal cooling. This archetype represents subtropical or regions with low demand for space heating, and high seasonal demand for cooling. R2 regions are also characterized by high solar PV capacity factors. R2 regions include Mexico and Australia.



**Figure A1. Four archetypal power systems cover a range of renewable resource quality and seasonal demands**




Source: KAPSARC Global Degree-Days Database.
Note: PV = photovoltaic; Argentina (ARG); Australia (AUS); Brazil (BRA); Canada (CAN); China (CHN); France (FRA); Germany (DEU); India (IND); Indonesia (IDN); Italy (ITA); Japan (JPN); Republic of Korea (KOR); Saudi Arabia (SAU); South Africa (ZAF); Turkey (TUR); United Kingdom (GBR); United States (USA).

- R3: seasonal heating. This archetype represents temperate regions with significant demand for space heating, and low seasonal demand for cooling. R3 regions are characterized by lower solar PV capacity factors and higher wind capacity factors. R3 regions include the United Kingdom and Germany.
- R4: high seasonal heating. This archetype represents colder temperate or subpolar regions with very significant demand for space heating, and no seasonal demand for cooling. R4 regions are characterized by very low solar PV capacity factors and higher wind capacity factors. R4 regions include Canada, and Kazakhstan.

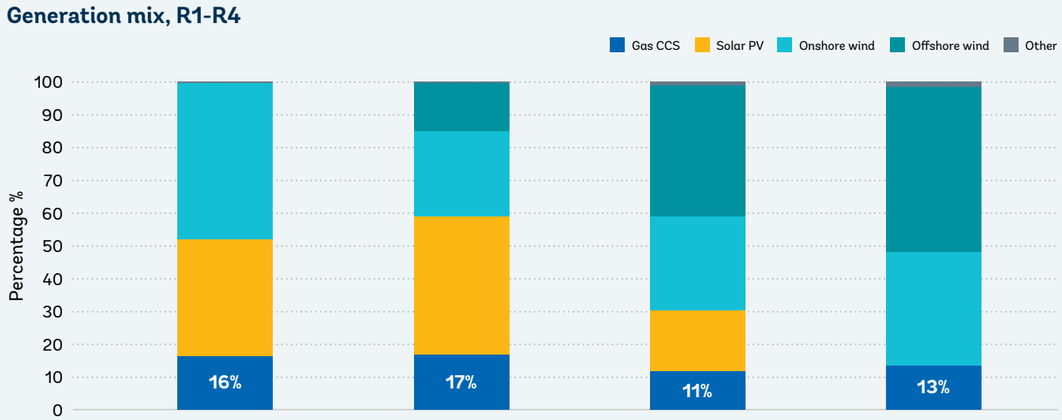
The four archetypal decarbonized electricity systems covering different climate types were modelled to understand the role of gas CCUS in the future generation mix across multiple national electricity systems. The objective of the archetypal systems is to characterize the role of gas CCUS across two major drivers of variation: the profile of climate-driven seasonal demand variation, and the mix of variable renewables best suited to geographies.

Figure A2 identifies the generation mix that could meet electricity demand at least cost across the four archetypal regions modelled in this study under moderate gas prices, defined as gas prices around $5/MMBtu.[85]

These modeled results indicate the role that gas CCUS could play in power systems characterized by moderate gas costs and limited nuclear or hydro generation. The archetypal electricity systems are based on constraints on nuclear and hydro, reflecting the expectation that these technologies will be constrained by availability of high-quality hydro resources, and the social and environmental impacts of new hydro developments. To characterize the role that gas CCUS could plan in power systems characterized by low or high gas costs, or a material share of nuclear or hydro generation, further sensitivities were modelled. Figures A3 and A4 identify the generation mix that could meet electricity demand at least cost under low or high gas costs, or a material share of nuclear or hydro generation, respectively.

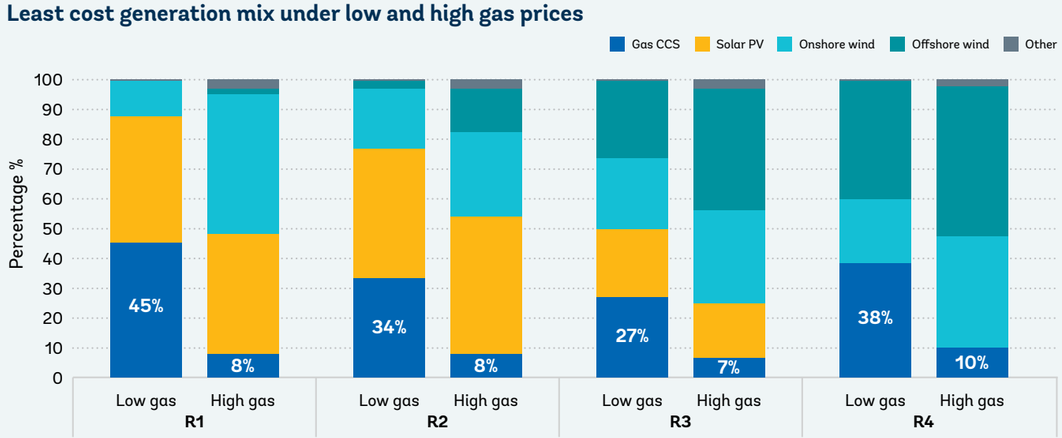
85 The base case $5/MMBtu gas price in the power generation analysis was determined by looking at the 5-year average values for gas prices in key countries. $5/MMBtu is the average value for medium-cost countries. Outside the power sector, gas prices are modelled endogenously based on gas resources and extraction costs in each region. This will be clarified in the report.

**Figure A2. Gas CCUS could account for 10–20% of generation in a 1.75°C scenario**




Source: Original compilation using the Imperial College WeSIM model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.

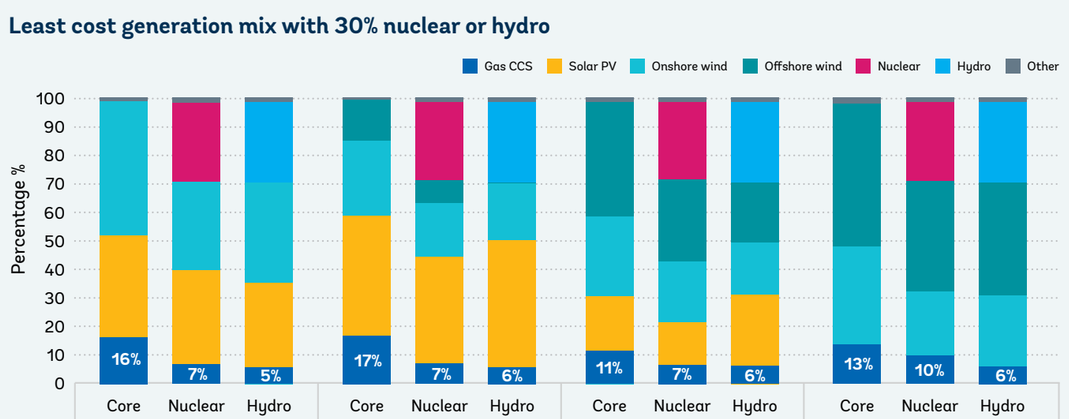
**Figure A3. The role of gas CCUS in power will be strongly driven by regional gas prices**




Source: Original compilation using the Imperial College WeSIM model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.



**Figure A4. The role of gas CCUS is smaller in the presence of substantial nuclear and hydro generation**




Source: Original compilation using the Imperial College WeSIM model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; PV = photovoltaic.

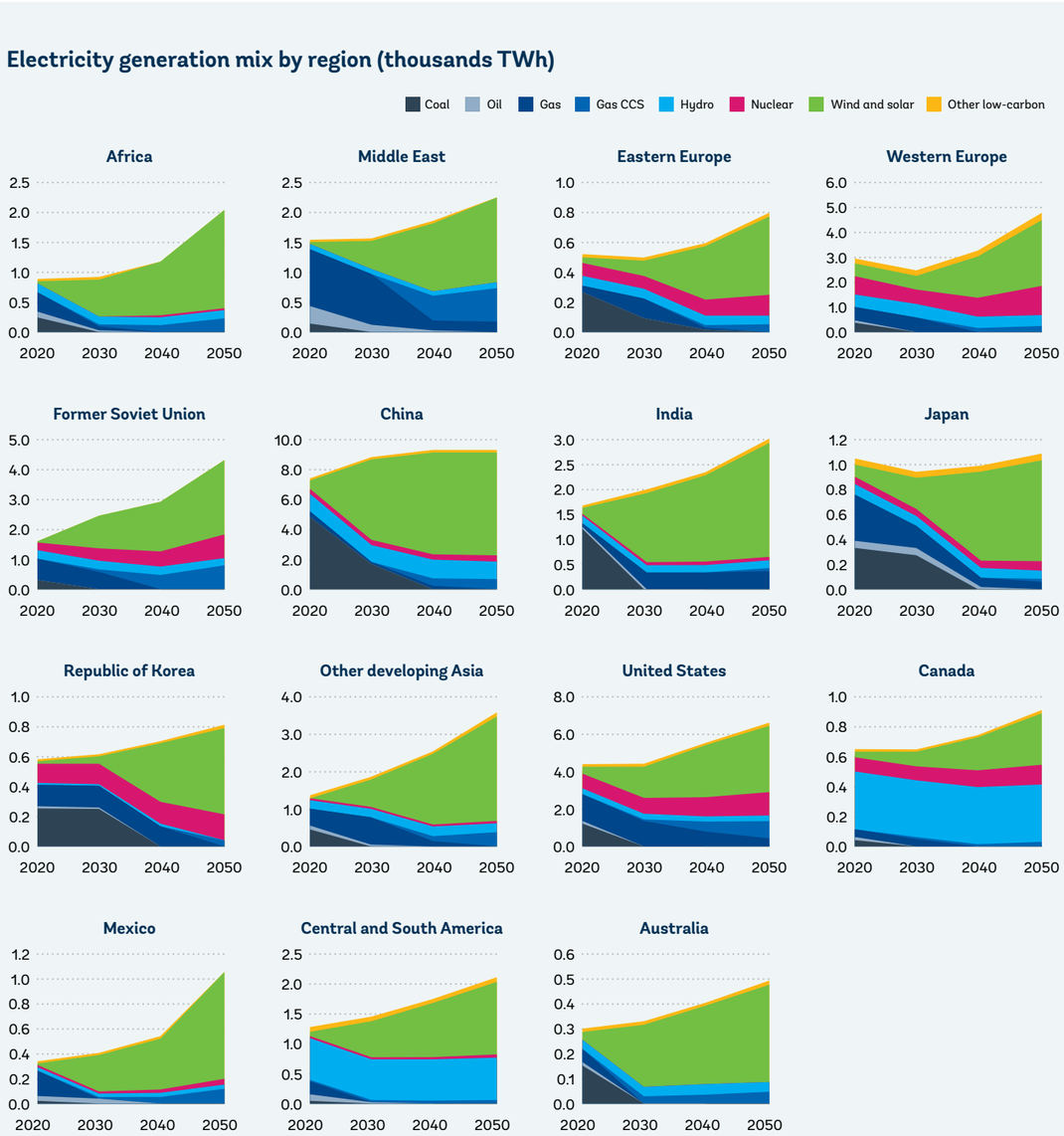
The following steps were then carried out to estimate the role of gas CCUS in each region:

1. Each region was mapped to its most appropriate archetype, that is, R1: year-round cooling; R2: seasonal cooling; R3: seasonal heating; R4: high seasonal heating.
2. Electricity generation from unabated coal, gas, and oil was taken from the power sector pathways developed in the TIAM whole energy system modelling described in section 2.
3. The share of gas CCUS in the generation mix at the time a region achieves net zero emissions in the TIAM modelling is set at the level specified by the WeSIM electricity model for that combination of archetype and gas prices, based on the core results and gas price sensitivities described above.
4. For regions with material nuclear or hydro generation, the share of gas CCUS in the generation mix at the time a region achieves net zero emissions is adjusted to account for the reduced need for gas CCUS in such regions, based on the nuclear and hydro sensitivities described above.
5. The share of gas CCUS in the generation mix at the time a region achieves net zero emissions is taken as the share of dispatchable generation that is needed in each time period.
6. Between 2020 and the net zero year, the share of gas CCUS is set such that this minimum level of dispatchable generation (unabated coal, gas, oil, and dispatchable gas CCUS) is met in each time period.[86]

Finally, the generation mixes for each region are aggregated to generate the global generation mix.

86 Assessing the dispatchable generation - the modelling takes into account that storage enables wind and solar to achieve partial dispatchability, and there are large volumes of wind and solar deployed in the modelling. However, there is a limit to the dispatchability of these technologies given the scale of storage needed. Further, biomass and nuclear have limited dispatchability either due to economics (biomass) or operational constraints (nuclear). The volume of gas CCUS in the net zero year is modeled based on the relative economics of this and other technologies, and these relative economics are also assumed to apply prior to the net zero year.

**Figure A5. The regional role of gas CCUS in power will vary, driven by gas prices and alternative firm power sources**




Source: Original compilation using the Imperial College WeSIM model.
Note: CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; Africa (AFR); Australia (AUS); Canada (CAN); Central and South America (CSA); China (CHI); Eastern Europe (EEU); Former Soviet Union (FSU); India

## Section 3: Estimating the national gas CCUS opportunity

The national gas CCUS opportunity was estimated for the four key opportunities considered in this study: industry, power generation, natural gas production, and low-carbon hydrogen production and use. For industry and power, the national gas CCUS opportunity was estimated by decomposing the regional industry and power opportunities modelled in this study to the country level. For industry, the national gas CCUS opportunity was estimated based on the current industry fuel mix, and the regional industry opportunities modelled in this study:

- The 2020 industry energy mix is taken from the International Energy Agency's World Energy Balances. As the latest published data is for 2018, this is used as a proxy for 2020 data.
- Total industrial energy use is assumed to grow at the same rate as for the wider region. For example, for Indonesia, the growth rate of industrial energy use is assumed to equal that of the "Other Developing Asia" region.
- The rate of growth of fuel shares in the energy mix is also assumed to follow a similar profile as for the wider region.

For power generation, the national gas CCUS opportunity was estimated based on the current generation mix, and the energy system modelling results for the archetype that best fits the country in question. [87] For natural gas production, the national opportunity was estimated for each country, based on national gas production, the $CO_2$ density of the natural gas, and the share of LNG in gas production:

- The CCUS opportunity is defined as the $CO_2$ that must be captured or vented in order to satisfy $CO_2$ content for pipeline gas or LNG. A maximum $CO_2$ level of 2 percent is assumed for pipeline gas, and of 0.2 percent for LNG.
- In countries with $CO_2$ content data available for some gas fields, the weighted average $CO_2$ content for these fields is assumed to apply to all gas produced in that country.
- In countries with no $CO_2$ content data available, the weighted average $CO_2$ content for global fields is assumed to apply to all gas produced in that country.

For low-carbon hydrogen production, the national gas CCUS opportunity was estimated based on the energy system modelling results for clean hydrogen demand, production mix of low-carbon and renewable hydrogen, and the country archetype (constrained gas user, large gas user, or gas exporter). For constrained gas users, the opportunity is estimated based on ammonia and methanol production only; for large gas users, the opportunity is estimated based on overall demand for clean hydrogen across industry and transport; and for gas exporters the opportunity is extended to cover low-carbon hydrogen production for export.



87 Detailed electricity system modelling was carried out to analyse the role of gas CCUS in the future generation mix across multiple national electricity systems. To characterize the role of gas CCUS in the future generation mix across the 15 major countries and wider regions considered in this study, this study modelled four archetypal electricity systems that span the range of output of variable renewables and the variation in electricity demand that are expected to determine the role and value of CCUS. Archetypes are listed here and explained in detail in chapter 2.4 of the main report: R1: Year-round cooling, R2: seasonal cooling, R3: seasonal heating, R4: high seasonal heating.



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