CCUS as a Tool for LNG Innovation

A report prepared for the
Global Gas Innovation Roundtable
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GLOBAL GAS
INNOVATION ROUNDTABLE

Prepared by

CANADAWEST
FOUNDATION

About the
Global Gas Innovation Roundtable

The mission of the Roundtable is to ensure that governments, policymakers, multilateral institutions and energy thought leaders have a greater understanding of the technology and innovation underway that will improve the performance – environmental and otherwise – of the gas sector.

It will raise the profile of gas technology and innovation through a variety of live and digital touchpoints, including the sharing of leading practices, highlighting emerging technology research and innovation, and profiling the array of events underway at any time around the world.

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1.0 Introduction

Purpose of this document

Natural gas and LNG have the potential to lower greenhouse gas (GHG) emissions from end-use when they displace higher-emitting sources, such as coal, that are used for power generation and industrial purposes. However, the production of LNG is very energy-intensive and can produce significant emissions, a fact often used to undermine the downstream benefits.

Several options exist for how LNG producers can lower emissions. These include electrifying operations, fuel switching to hydrogen, and employing carbon capture, utilization and storage (CCUS) to capture CO_2 emissions: all promising technologies that fit different circumstances.

This report examines CCUS as a potential path forward for global LNG producers. This report describes what CCUS is, describes how it is being used, how it fits with LNG production, and how governments can support its adoption. The report also presents four case studies that highlight different features of CCUS projects and the factors that lead to success or failure.

But although CCUS holds a lot of promise, it isn't a perfect solution—so this report also presents the complexities and difficulties, from technology to costs, that make the uptake of CCUS challenging.

2.0 What is CCUS?

> “Carbon capture, storage and utilisation play a critical role in achieving climate goals...Limiting the availability of CO_2 storage would increase the cost of the energy transition.”
>
> — International Energy Agency[1]

CCUS stands for Carbon Capture, Utilization, and Storage.*

As shown in *Figure 1*, CCUS is a set of technologies that capture CO_2 emissions from industrial sources such as power plants and other industrial facilities, compress and transport it (usually via pipeline), and then permanently sequester the CO_2 by injecting it underground (normally at depths of two kilometres or more) or embedding it in physical products.

As described in the next section, CCUS has been in use since the 1980s, and is a technology that is real, safe, proven, and can be applied at a very large scale. CCUS is a particularly useful solution for hard-to-abate sectors that have high emissions from a fixed point and few options to directly reduce carbon dioxide output.

Many organizations that evaluate energy and emissions pathways have publicly stated that the use of CCUS is essential to reaching a low-emissions future.

- The **Intergovernmental Panel on Climate Change (IPCC)**, a United Nations body, has stated that CCUS is a key technology for reducing greenhouse gas emissions and achieving global climate goals.[2]
- The **International Energy Agency (IEA)** has identified CCUS as a “critical technology” to reach carbon neutrality by 2050.[3]
- The **United Nations Framework Convention on Climate Change (UNFCCC)** has identified CCUS as a key technology to achieve long-term decarbonization of the energy sector.[4]
- The **World Resources Institute (WRI)** has identified CCUS as critical to reduce emissions from hard-to-abate industrial sectors, particularly cement and steel.

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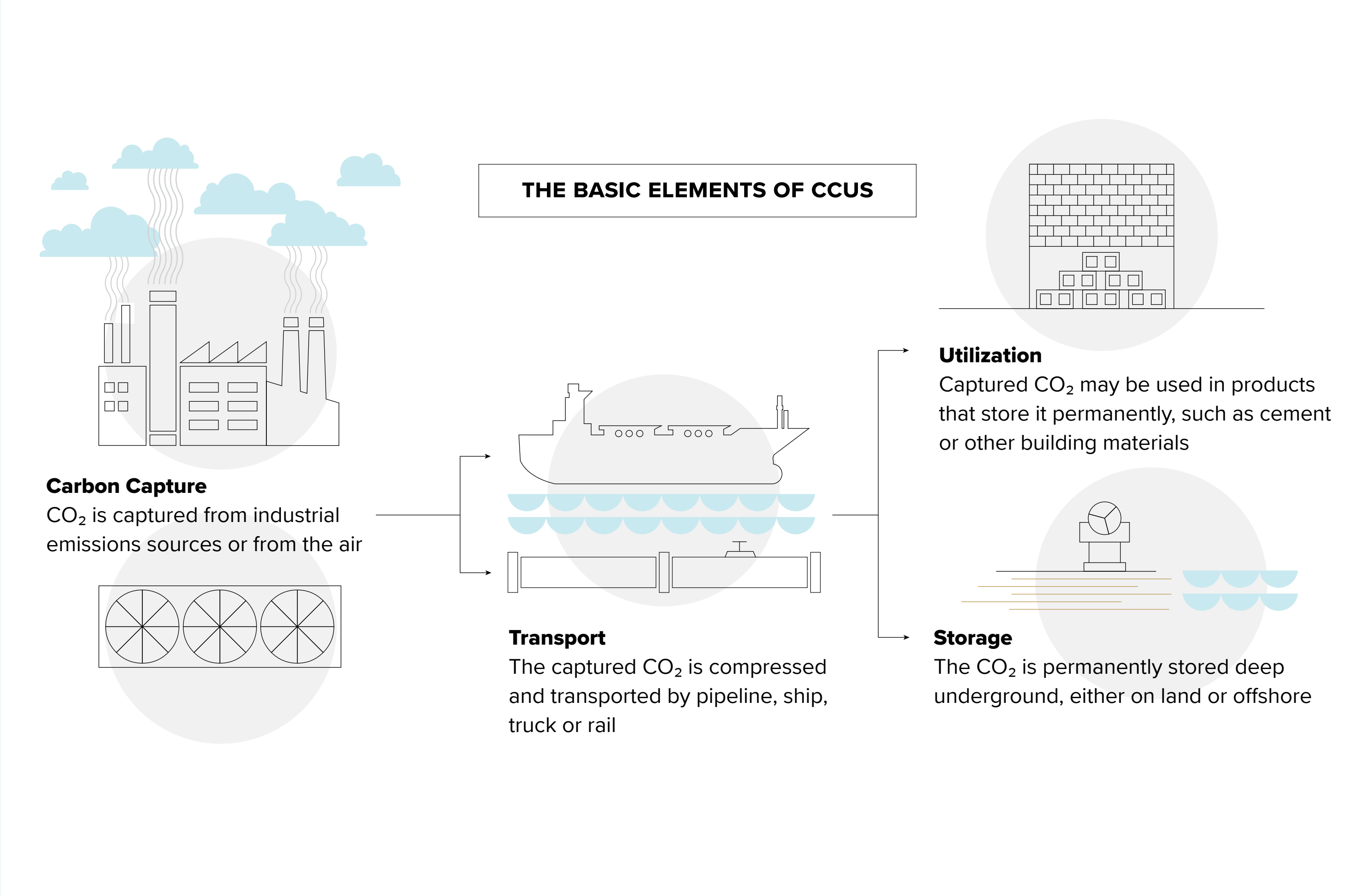
* CCS stands for Carbon Capture and Storage. CCUS adds an extra “U” for utilization. CCUS is the broader term, since it allows for more possibilities around how captured emissions may be used. However, in practice, most captured CO_2 emissions are sequestered, not used, which means CCS is often the more accurate term. In this paper, CCUS is used except where CCS is specifically meant, or in project names that use CCS.

Figure 1: The Basic Elements of CCUS



Carbon Capture
CO_2 is captured from industrial emissions sources or from the air

Transport
The captured CO_2 is compressed and transported by pipeline, ship, truck or rail

Utilization
Captured CO_2 may be used in products that store it permanently, such as cement or other building materials

Storage
The CO_2 is permanently stored deep underground, either on land or offshore

Source: Adapted from the International Energy Agency.

3.0 The Global Rise of CCUS

History

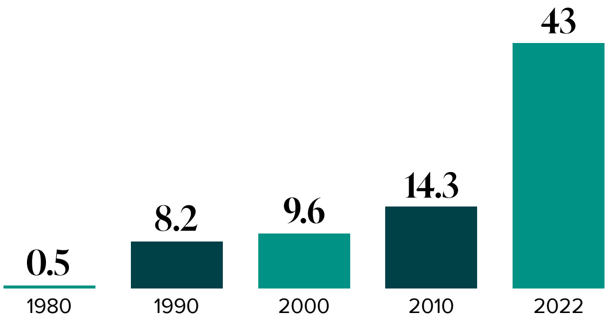
An old technology

The concept of CCUS is not new. Since the 1920s, carbon dioxide has been removed as waste from raw natural gas when it is processed. And since the 1970s, captured CO_2 has been injected into producing oil fields to increase pressure and extract remaining oil—a process known as enhanced oil recovery (EOR).[5] However, despite its long history, only 10 commercial CCUS facilities existed worldwide by 2010 with a total capture capacity of just 13 megatonnes (Mt) of CO_2.[6]

Recent and rapid growth

Since 2010, technological advances, private and public sector climate commitments and favourable government policy have led to a rapid rise in the development of CCUS projects. As of September 2022, there were 30 commercial facilities operating globally with a capture capacity of 43 Mt CO_2 (see *Figure 2*) and another 164 facilities in various stages of development.[6] In addition to commercial facilities, close to 90 pilot and demonstration facilities have been constructed.[7]

Figure 2: CO_2 capture from commercial CCUS facilities in operation globally (Total capacity – Mt CO_2)



Source: IEA[8] and Global CCS Institute[6]. Note: Does not include pilot projects, demonstration facilities or facilities that are pre-operational or underused capacity of operational plants.

As of Sept. 2022:

30

commercial CCUS facilities globally

164

in development

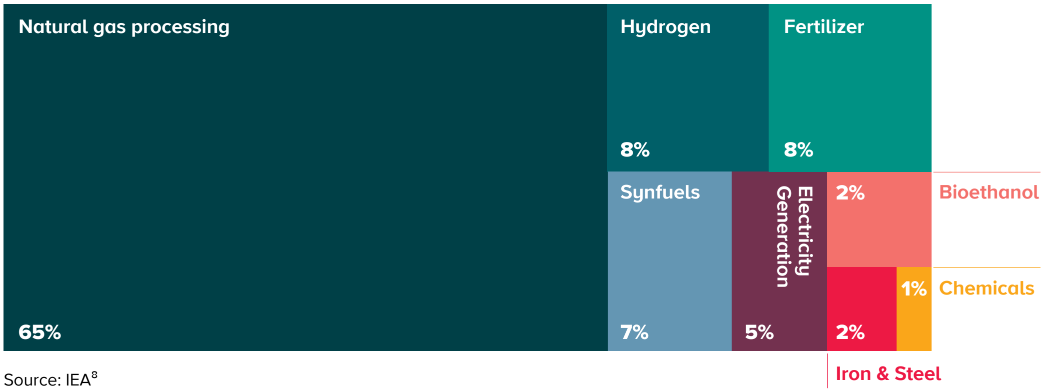
90

pilot and demonstration facilities

An expansion of use cases

Due to advances in technology, the possibilities for different industries to implement carbon capture have also expanded significantly. While natural gas processing is still the primary application for CO_2 capture, the technology has now successfully been deployed in a wide range of industries including hydrogen, fertilizer, concrete, biofuels, synfuels, electricity generation and iron and steel (see *Figure 3*).

Figure 3: CCUS facilities by industry type, 2021



Source: IEA[8]

More CCUS will be needed to reach net zero goals

In its flagship 2020 report, the IEA has stated that "Reaching net zero will be virtually impossible without CCUS."[9] In the report's Sustainable Development Scenario, under which net-zero is reached by 2070, CCUS will need to remove over 840 Mt per year of CO_2 by 2030, 5,600 by 2050 and 10,400 by 2070. Although the implementation of CCUS projects has increased dramatically over the past decade more work is still required.

Locations

To date, CCUS development has primarily occurred within a few key countries and regions—namely the United States, Norway, the United Kingdom, Canada and Australia.[7]

Several factors contributed to the early success of these regions. First, they all had existing oil and/or gas industries. This provided large and high-volume emissions sources from an industry that was looking to decarbonize, the geological and industrial know-how required for CCS development, and opportunities to use the captured carbon for enhanced oil recovery (EOR). Second, these countries had governments that that enacted policies to favour CCUS development, provided direct and indirect funding for projects (see Section 7), and established regulatory frameworks required for commercial CCUS development. This helped unlock access to large sums of private-sector capital. And finally, these countries all had access to the geological conditions required to permanently sequester CO_2 in large quantities.

Other countries are coming onboard. China and India have projects under development, and countries without oil and gas are developing projects for capture from coal-fired electricity generation (e.g., Japan) or industrial clusters (e.g., Ireland).

4.0 How CCUS Works

CCUS involves three component activities: a) capturing emissions, b) transporting emissions, and then c) disposing of those emissions, either in a product such as cement, soap or renewable fuel, or by sequestering them underground.

4.1 Capture

Carbon dioxide can in theory be captured from anyplace it exists, whether that is industrial emissions, combustion products from buildings, or even directly from the air itself. However, capture is more efficient and costs are lower when the CO_2 is more highly concentrated and available in large volumes. This is why industrial emissions are a prime source. As an example, the CO_2 concentration in emissions from an ethanol plant is around 90%; the emissions from a cement plant is around 15%, and the air itself has a concentration of around 0.04%.

The types of industrial activities where CCUS is most commonly employed include:

- Power generation that burns hydrocarbons
- Iron and steel production
- Cement production
- Fertilizer production
- Hydrocarbon refining (natural gas, ethanol, methanol, petrochemicals, etc.)
- Waste incineration

The methods used for capture include:

Post-combustion capture

Post-combustion capture is used for CO_2 emissions that are produced from the combustion of fossil fuels (e.g., burning natural gas or coal). The flue gas (also known as the exhaust gas) is directed to a carbon capture unit, where it comes into contact with a solvent that selectively absorbs the CO_2. The solvent typically used is an amine solution, which has a high affinity for CO_2. The solvent is then re-heated to release the captured CO_2, which is compressed and transported for storage or utilization. The solvent is recovered so that it can be used again.

Pre-combustion or industrial capture

Pre-combustion capture allows CO_2 to be removed from gases in circumstances where no combustion will happen, or where it hasn't happened yet—such as may happen in chemical refining, fertilizer production, in gasification-based power plants, etc. Processes such as partial oxidation or steam methane reforming are used to produce a synthetic gas. This is then converted to a mixture that is primarily CO_2 and hydrogen. The CO_2 is captured and removed, leaving hydrogen behind.

Post-combustion and pre-combustion carbon capture fit different circumstances. They also have different benefits and drawbacks.

- Post-combustion capture:
  → can be retrofit onto existing industrial plants
  → is a more mature technology
- Pre-combustion capture:
  → generally requires a new build
  → is typically more complex and expensive
  → generally has higher CO_2 concentration, and therefore can achieve higher overall efficiency
  → can produce hydrogen as a by-product

Direct air capture

Direct air capture (DAC) extracts CO_2 directly from the atmosphere, using fans to move large quantities of air. There are only 18 DAC plants worldwide, and most of them operate at small scale and produce CO_2 for utilization, such as in carbonated drinks, or to be refined as syngas.[10] Together, all the DAC plants in operation sequester 0.01 Mt CO_2 /year. The International Energy Agency's Net Zero by 2025 scenario would require DAC to remove 60 Mt CO_2/year by 2030—a massive scale-up.

All of these processes—pre-combustion capture, post-combustion capture and direct air capture—result in CO_2 being output as a compressed gas. What happens to that gas is discussed below under Transportation. But it is useful to note that there are a number of companies commercializing technologies that instead produce solid carbon in forms such as carbon black and carbon nanotubes. This solid carbon can—at least in theory—be used in applications such as steel production, agriculture or as an input to other industrial processes. These companies are not yet capturing CO_2 at a large scale. However, they are something to watch for the future, because instead of capturing a waste product, they are creating a new value stream.

4.2 Transportation

Compressed CO_2 can be transported by pipeline, ship, truck or rail. Pipeline is the most common method.

Transporting CO_2 by pipeline has many similarities with transporting natural gas, but there are some differences in terms of pipeline construction, design and the transport process itself as well as the management of the pipelines for integrity and safety.[11] CO_2 is non-flammable and the main safety concern is suffocation in confined spaces and the effects of impurities. CO_2 pipelines have been in operation for decades to move carbon dioxide to Enhanced Oil Recovery facilities. 5,000 miles of such pipelines exist in the U.S., where they are regulated like pipelines for other hazardous liquids.[12]

Transporting via ship, truck or rail are also viable ways to transport compressed CO_2. These options are more costly than pipelines, but may be reasonable when the sources and storage sites are too far apart for pipelines to link or the volumes of CO_2 to be transported are too small or intermittent for a pipeline.

4.3 Utilization/sequestration

Once CO_2 has been delivered, it can either be used for a specific purpose or sequestered underground to dispose of it. Both approaches prevent the CO_2 from escaping into the atmosphere.

Utilization

Rather than treating the CO_2 as a waste product, utilization treats it as a value-added product.

However, despite much research and prize money[13] offered, few large-scale solutions have been found. The most promising use is in concrete, where CO_2 is injected to make the concrete stronger. Given the enormous amount of concrete used worldwide each year (it's the most widely produced product on Earth), this is a constructive development.

A few other good co-uses have been identified—like using it to produce tomatoes, cucumbers or beer. Many greenhouses import CO_2 to help vegetables grow; some are starting to co-locate with industrial emitters, and the transfer of carbon dioxide from one to the other benefits both.[14] Some breweries are also starting to experiment with capturing their own emissions and using that to replace purchased CO_2.[15] Finally, carbon fibre is a substance that has a wide variety of potential applications but is currently scarce and expensive and could theoretically be created from captured CO_2 emissions. None of these applications, however, have the potential to use CO_2 at the volume at which it is being produced now, or the greater volumes anticipated in the future.

As a result, most captured CO_2 needs to be sequestered.

Sequestration

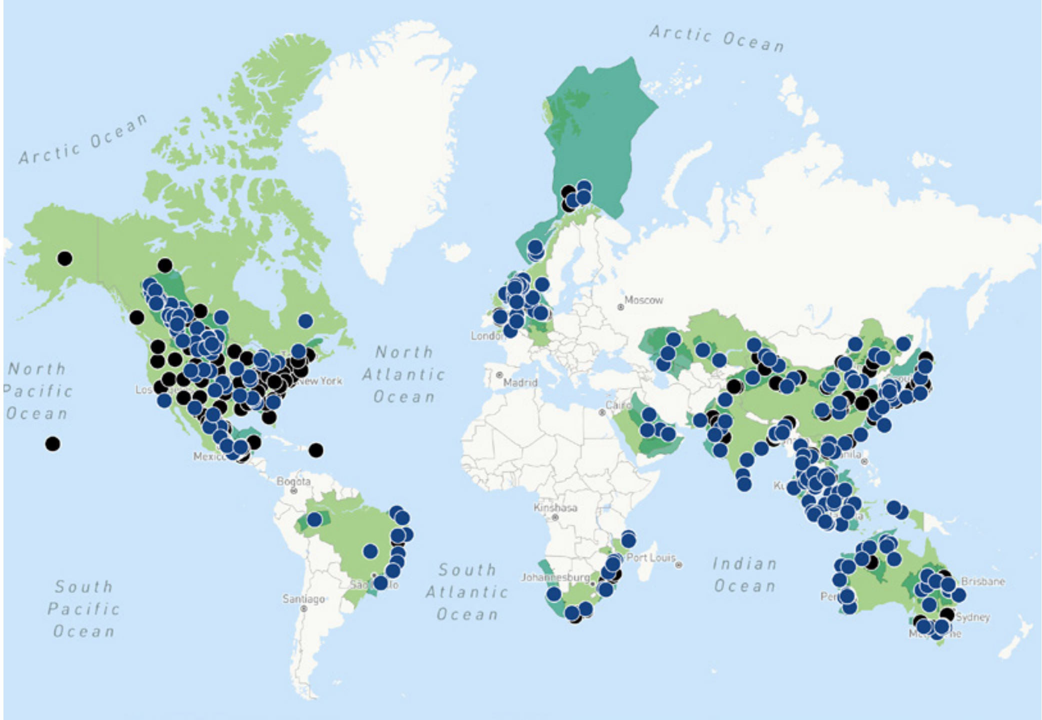
Carbon sequestration is the process of injecting CO_2 deep underground (typically at a depth of 2 km or more), where it eventually mineralizes and turns into rock. This disposal method is essentially permanent, with around 99% of the CO_2 projected to remain in place for 1,000 years.[16]

However, not all geologies are equally appropriate for this solution. The rock needs to be porous and permeable (like sandstone or limestone), deep underground so that it doesn't touch groundwater, and covered by a "cap" of impermeable rock so the gas can't escape. The Oil & Gas Climate Initiative (OGCI) has created an excellent resource (shown in *Figure 4*) that evaluates where underground storage is appropriate.

But good geology alone is not enough. Like oil and gas production, sequestering carbon underground requires drilling, and access to a common resource (in this case, "pore space"). This is generally only possible to do after a government has created a legal and regulatory framework for CO_2 storage and has trained its regulators to undertake technical assessments.

Transporting and sequestering CO_2 may be done by the company that produces the emissions. Commonly, however, it is done by a third party, with complex financial arrangements between the emitter and the sequesterer to cover costs and share benefits.

Figure 4: **Global regions with geological storage potential**



Source: Oil & Gas Climate Initiative (OGCI)[17]. Note: Countries in white have not yet been evaluated. OGCI estimates global evaluation will be complete by 2025.

A "Playground" to Test CO_2 Sequestration Safety and Permanence

Carbon Management Canada's Newell County Facility is a site like nowhere else on earth. Located in southern Alberta, Canada, the facility exists to answer the question of **"how can we inject CO_2 underground safely and efficiently, and ensure it stays where it's supposed to?"**

Most large-scale CCUS demonstration sites around the world inject CO_2 several kilometres below the surface. The facility looks at the tougher question – what happens if something goes wrong? It was created to mimic a leak from a shallow storage reservoir and to test monitoring technologies capable of accurately tracking the behaviour of the escaped CO_2. There is no other site in the world that offers the opportunity to use sophisticated technologies to study CO_2 behaviour in this way. As a result, the facility plays host to numerous international teams who come with research questions and technology that they want to test under extreme conditions.

At the site, researchers have access to a combination of state-of-the-art instruments and monitoring equipment that includes not only traditional seismic testing, but also fibre optic strain and temperature monitoring, resistivity mapping, electrical tomography and mass spectrometry. Any organization can partner with the facility and gain access to a viable working model to test their CCUS activities, as well as 5+ years of data to compare their methods against.

Through the Newell County Facility, Carbon Management Canada hopes to advance government and public trust that CO_2 sequestration is safe and permanent—and hopefully to lead to new commercial sequestration approaches that can be used safely in a wider variety of geologies, and with low environmental impact.

Enhanced Oil Recovery

A final use for CO_2 is Enhanced Oil Recovery (EOR) which combines features of both utilization and storage.

EOR is a technique that injects CO_2 or other pressurized fluids into an oil reservoir to extract additional oil after other recovery methods have been exhausted. It is very effective in getting the oil out, and can extract an additional 30-60% of a reservoir's volume.

It is also very effective at sequestering carbon dioxide. Around 300-600 kg of CO_2 is injected underground for each barrel of oil produced. Given that the full lifecycle of a barrel of oil is around 500kg of CO_2, EOR using captured carbon dioxide can be carbon neutral – or even net negative.[18] However, most of the CO_2 currently used in EOR is not derived from CCUS, but from naturally occurring underground CO_2 deposits. In this case, there is no emissions reduction benefit.[18]

4.4 Hubs – combining resources and lowering costs

Because CCUS projects are very large, expensive and take a long time to plan, permit and build, many countries are advancing a "hub" approach, where transportation, storage and sequestration infrastructure resources are shared across capture projects – including proponents from different industries.

A hub approach allows the costs and risks to be shared, and also helps to achieve economies of scale that brings down the cost and increases the feasibility for all users, including small volume emitters. Many CCUS hub projects are "open access" to allow a wide range of users to add their emissions to the transportation and storage networks, including some whose emissions would be too small to do a CCUS project alone.

Table 1 shows examples of existing CCUS hubs.

Where could more hubs go?

The Oil & Gas Climate Initiative (OGCI) has mapped areas across the globe that are suitable for developing hubs. "It does this by matching clusters of CO_2 sources from a range of emitting industries with possible storage locations. It then defines possible hub areas based on estimates of cost per tonne, including capture, transportation and storage."[19] OGCI has so far identified 279 potential CCUS hubs in 56 countries.

Table 1: Examples of CCUS hubs

Name	Location	Owner / Consortium Partners	Capture – which industries	Transport	Storage	Capacity (MT CO_2/yr)
Alberta Carbon Trunk Line	Canada	Wolf Midstream	Fertilizer, Refineries	Pipeline	EOR	1.8 (14.6 max)
Aramco Jubail CCS	Saudi Arabia	Aramco, Linde, SLB	Industrial, Natural Gas	Pipeline	Saline Aquifer	9
Aramis	Netherlands	TotalEnergies, Shell, EBN, Gasunie	Chemicals, Incinerators, Refineries, Steel	Pipeline/ Ship	Depleted Gas Field	5
Antwerp@C	Belgium	Air Liquide, BASF, Borealis, ExxonMobil, Fluxys, INEOS, Port of Antwerp-Bruges, TotalEnergies	Ammonia, Hydrogen	Pipeline/ Ship	Depleted Gas Field	1.5
HyNet North West	UK	Cadent, CF Fertilisers, Eni UK, Essar Oil UK, Hanson UK, Inovar, Progressive Energy, University of Chester	Cement, Fertilizer, Hydrogen, Refineries	Pipeline	Depleted Gas Field	4.5
East Coast Cluster	UK	BP, Equinor, National Grid, Shell, TotalEnergies	Aviation Fuel, Building Materials, Chemicals, Hydrogen, Incinerators, Industrial Heat, Power, Refineries	Pipeline	Saline Aquifer	27
Northern Lights	Norway	Equinor, Shell, TotalEnergies	Biomass, Cement, Fertilizer, Hydrogen, Incinerators, Refineries, Steel	Pipeline/ Ship	Depleted Gas Field	5
Porthos	Netherlands	Air Liquide, Air Products, ExxonMobil, Shell	Hydrogen, Refineries	Pipeline	Depleted Gas Field	2.5
Junggar Basin	China	China National Petroleum Corporation	Cement, Chemicals, Power	Truck/ Pipeline	EOR	3
Ravenna CCS	Italy	Eni, Snam	Cement, Ceramics, Chemicals, Steel, Waste-to-Energy	Pipeline	Depleted Gas Field	10
Liberty Louisiana	USA	Shell	Ammonia, Biofuels, Biomass, Cement, Paper, Petrochemicals, Steel	Pipeline	Saline Aquifer/ Depleted Gas Field	N/A

Sources: OGCI[20], CBC[21]

Figure 5: **Global regions with CCUS hub potential**

Source: OGCI[19]

5.0 Case Studies

Four case studies are presented below to provide a rounded picture of how CCUS is being used today. The four cases highlight different features of CCUS projects, including where emissions are sourced and sequestered, how projects are organized and funded, and what factors led to success or failure.

CASE STUDY 01

Quest CCS – Government funding drives knowledge sharing & lowers costs

Completed in 2015, the Quest CCS project was the world's first commercial-scale application of CCS to oil sands upgrading. The project uses amine technology to capture CO_2 from hydrogen manufacturing units (steam methane reformers) at the Shell Scotford Upgrader, a facility that processes raw bitumen from the Alberta oil sands into synthetic crude oil. Once captured, the CO_2 is compressed and transported 65km via pipeline to the injection site where it is stored 2 km below ground. Over the course of its life, the project has captured and permanently stored over eight million tonnes of CO_2.

In addition to being a pioneer CCUS project for oil sands upgrading, Quest is an excellent example of how public sector funding can drive increased knowledge sharing. As part of its funding agreement with the governments of Canada and Alberta, Shell is required to share its learnings with the province on an annual basis, with the goal of advancing future CCUS projects and informing policy decisions within the province. This includes publishing a publicly-available annual project summary report that present lessons learned and the challenges and successes the project has faced throughout the year. The project proponent must also participate in conferences, host workshops and publish other findings as requested.

The value of this information is not small. Shell estimates that, based on its learnings from Quest, a similar project could be built today for 30% lower cost. Government support at this early stage has clearly helped CCUS move along the experience curve, benefitting future projects.

Project type and location

- Project type: Oil sands upgrader
- Project proponent/operator: Shell, on behalf of the Athabasca Oil Sands Project
- Location: Alberta, Canada

Capture and storage

- Emission source: Hydrogen production (auto thermal reforming)
- Capture technology: Amine absorption
- Storage type: Dedicated geological storage

Volumes

- Start of operations: 2015
- Capacity: >1 Mt/year
- Sequestration to date: 8+ Mt
- Percent of emissions captured: 35% of upgrader emissions

Costs

- Cost of capture: $80/tonne
- Capital cost: CAD $1.35 billion
- Funding: $865 million in government funding

CASE STUDY 02

Longship – An international, open-source hub requires massive coordination

The Norwegian government has called the Longship CCS project “the greatest climate project in Norwegian industry ever.” Once complete it will be the world’s first open-access cross-border CCUS hub, providing sequestration for a wide range of hard-to-abate industries across Europe. The project has been primarily funded by the Norwegian government as part of its efforts to reduce emissions from Europe as a whole. International access to the project will be enabled by the use of ships to transport CO_2 from capture sites to a receiving terminal in Øygarden, Norway. The CO_2 will be temporarily stored at the terminal before being transported via pipeline to an offshore sequestration reservoir 2,600 meters below the seabed.

Phase one of Longship is expected to be completed in 2024 and will enable the permanent sequestration of 1.5 Mt of CO_2 per year. Contracts for offtaking CO_2 have already been established with three companies including a cement factory and a waste-to-energy plant in Norway and a fertilizer plant in the Netherlands. Phase two of the project will provide additional opportunities for emission reduction across Europe by expanding capacity to over 5 Mta by 2026. As of June, 2021, letters of intent have been signed with 11 companies, and dialogue is open with a further 60 companies across Europe that want to use the project to sequester emissions. Hubs like this one open the door to capture projects, creating a “common good” necessary to kick start the process.

Because this project is so broad in scope, a large number of organizations needed to coordinate their activity. To accomplish this complex task, Longship was organized as several individual sub-projects, led and executed by industrial partners, but within a framework coordinated and integrated by Gassnova, the Norwegian state enterprise for CCS.[22] Although the project was largely publicly funded, the Norwegian government itself does not own the facilities or infrastructure. A major sub-component of Longship is Northern Lights, the part of the project that transports and sequesters the CO_2 and that is operated by the oil companies Equinor, TotalEnergies and Shell.

Project type and location

- Project Name: Longship (Langskip)
- Project type: Open access CCUS hub
- Project proponent/operator: Gassnova and Northern Lights JV
- Location: Norway/International

Capture and storage

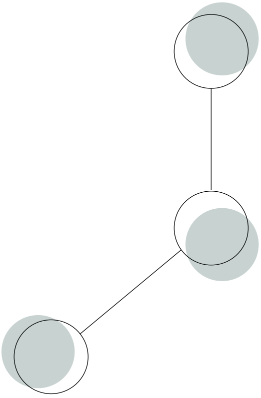
- Emission sources: Cement, waste to energy and fertilizer
- Capture technology: Amine absorption
- Storage type: Dedicated geological storage

Volumes

- Start of operations: 2024
- Percent of emissions captured: Site dependent
- Capacity: 1.5 Mt/year

Costs

- Cost of capture: Site dependant
- Capital cost: $2.7 billion
- Funding: Norway government contributed $1.85 billion



CASE STUDY 3

Al Reyadah / Abu Dhabi CCS – Smart choices in geography, capture and use

The Al Reyadah – Abu Dhabi CCUS project, completed in 2016, was the world's first use of commercial-scale CCUS in the iron and steel industry and the first commercial carbon capture project in the Middle East. The facility captures 800,000 tonnes of CO_2 per year (roughly 90% of total emissions) from a direct iron reduction reactor at Emirates Steel Industries' steel manufacturing complex. The CO_2 is separated from the reactor's waste stream using an MEA amine absorption system; then it is dehydrated, compressed and transported 43km to the Abu Dhabi National Oil Company (ADNOC)'s Rumaitha oil field for use in enhanced oil recovery (EOR).

Several factors contributed to the success of the project. The first is a value case: the captured carbon could be used by ADNOC for EOR, rather than needing to be sequestered. The second is location: the Emirates Steel plant which generates the emissions is located close to ADNOC's oil field where the CO_2 will be used. And third is a very carbon "rich" emissions stream: Emirates Steel's waste stream consists of around 99% CO_2.

Building on the success of the Al Reyadah facility, ADNOC has announced plans to expand capture operations to 5 Mt per year through another two phases of development. The first will aim to capture 2.3 Mt per year from the Shah gas processing plant and is expected to be operational in 2025. The second will capture an additional 2 Mt per year from the Habshan and Bab gas processing facility; no expected completion date has been announced yet for this phase. All three phases of development will ultimately sequester CO_2 in the same EOR reservoir.

Project type and location

- Project name: Abu Dhabi CCS/Emirates Steel Industries CCS Project/Al Reyadah
- Project type: Steel production
- Project proponent/operator: Abu Dhabi National Oil Company
- Location: Abu Dhabi, United Arab Emirates

Capture and storage

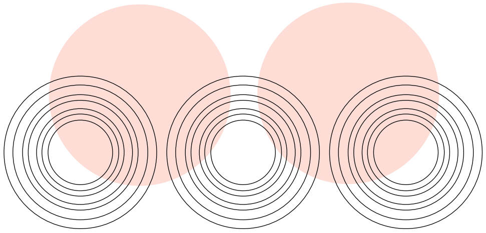
- Emission source: Direct Reduced Iron (DRI) plant
- Capture technology: MEA amine absorption
- Storage type: Enhanced oil recovery

Volumes

- Start of operations: 2016
- First capture: 2016
- Capacity: 0.8 Mt/year
- Percent of emissions captured: Up to 90% of emissions from Direct Reduced Iron plant

Costs

- Funding: Publicly funded by the government of Abu Dhabi through USD $15 billion Masdar City project



CASE STUDY 4

Gorgon CO_2 Injection – Technical challenges lead to underperformance

Australia's Gorgon CO_2 injection project is the world's largest CCS project using dedicated geological storage, with a capture capacity of up to four million tonnes of CO_2 annually. The project is co-located with Chevron's Gorgon LNG facility and is used to remove CO_2 from the gas produced in the Gorgon gas field, which can contain up to 14% CO_2, prior to liquefaction.

However, despite its enormous capacity, the project has underperformed since it began operations in 2016, due to a variety of technical challenges with the injection reservoir. Only 2.1 Mt was stored in 2021 —just 53% of the designed capacity.

The facility's challenges stem primarily from large volumes of water within the injection reservoir. As CO_2 is sequestered, water needs to be removed to ensure excess pressure does not build and cause fractures in the reservoir. However, corrosion and equipment failure have hampered the project's the ability to pump water from the system. This led to a three-year delay in sequestration start-up (2016-2019) and a regulatory order in 2020 to cut injection rates to one-third of total capacity. Due to these delays, Chevron missed its government-mandated emissions reduction targets by over 5 Mt and was forced to purchase carbon credits to cover the gap.

The Gorgon CCS project serves as a reminder that despite advances in carbon capture technology, subsurface conditions are extremely important for CCS projects.

Project type and location

- Project name: Gorgon CO_2 Injection Project
- Project type: LNG
- Project proponent/operator: Chevron/Gorgon Joint Venture
- Location: Western Australia, Australia

Capture and storage

- Emission source: Naturally occurring reservoir CO_2
- Capture technology: Amine absorption
- Storage type: Dedicated geological storage

Volumes

- Start of operations: 2016
- First sequestration: 2019
- Capacity: 3.3-4 Mt/year
- Sequestration to date: 7+ Mt
- Percent of emissions captured: 40% of total LNG plant emissions

Costs

- Capital cost: AUD $3.1 billion
- Funding: AUD $60 million contributed by gov't

6.0 LNG and CCUS: Is It a Good Fit?

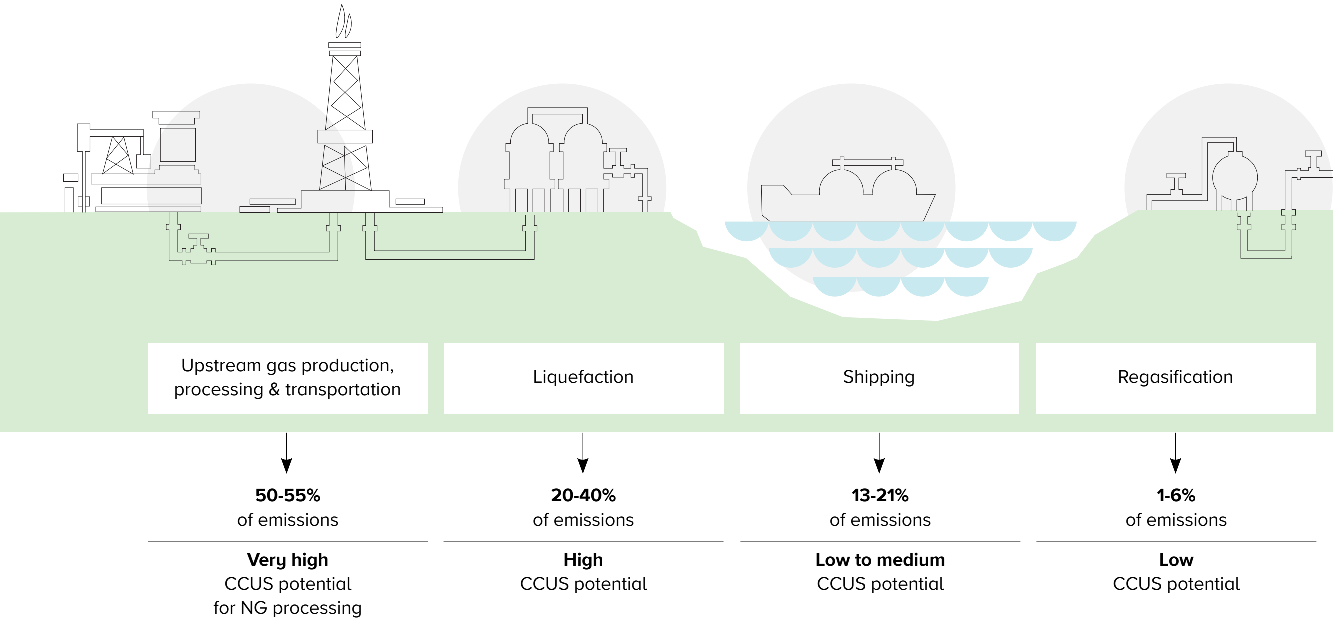
LNG is touted as a fuel that has the potential to lower global GHG emissions by displacing higher-emitting sources of power such as coal. But the LNG production process, from upstream gas extraction to downstream regasification, is itself very energy-intensive and can produce substantial emissions—equivalent to about one-third the emissions produced by the consumer combusting the LNG.

Both total emissions and emissions intensity differ enormously across LNG projects, depending on everything from how the gas is produced, to the energy source used for liquefaction, to how far it is shipped. The Wood Mackenzie LNG Carbon Emissions tool[23] compared emissions from a set of LNG projects across the world shipped to Tokyo. Emissions ranged from around 10 to almost 30 kilograms of CO_2 equivalent per mmbtu of gas.[24]

Along the LNG supply chain:[25-28]

- 50-55% of emissions come from upstream gas production, processing and transportation
- 20-40% come from liquefaction
- 13-21% come from shipping the LNG
- 1-6% come from the regasification process

Figure 6: **Emissions and CCUS potential along the LNG supply chain**



Source: Adapted from Herbert Smith Freehills[25]

Parts of the LNG supply chain are an excellent fit for CCUS, while other activities are not suitable. The table below explains where CCUS makes sense, where it doesn't, and why.

	CCUS POTENTIAL	
Upstream gas extraction	**Very low**	Upstream gas extraction from dispersed wellsites is not a good fit for CCUS.
Natural gas processing	**Very high**	There is a very strong value proposition for using CCUS for NG processing. CO_2 (and H_2S) must be removed during processing before liquefaction can take place. This means that extraction is already taking place (usually through an Acid Gas Removal Unit – AGRU), and represents little or no added cost. It is only sequestering CO_2 (as opposed to venting it) that would create additional cost.[26] For this reason, CCUS is already used or is being constructed for many natural gas processing facilities globally (see *Table 2*).
Transportation	**Low**	Although transportation (usually via pipeline) produces emissions, these tend to be small facilities (like compressor stations) spread out along the transportation corridor. This makes CCUS impractical. The IEA suggests electrification is a better option.[27]
Liquefaction	**High**	Liquefaction is a very good candidate for CCUS use because emissions are high and concentrated in one location. Wood Mackenzie estimates that CCUS can reduce the emissions from liquefaction by up to 90%.[24] Several CCUS projects for LNG liquefaction facilities already exist (Ras Laffan, Qatar; Snovhit, Norway; Gorgon, Australia) or are proposed (Sabine Pass, USA). Carbon capture at the liquefaction stage can be applied to emissions in the flue gas from gas turbines used to power the liquefaction process; or from emissions released in the generation of power for the remainder of the facility.[29] Emissions can be reduced through either pre- or post-combustion technologies, as discussed in Section 4.
Shipping	**Low to medium**	Using CCUS to reduce the emissions from marine shipping of LNG is technically feasible, but still in very early stages. The Oil & Gas Climate Initiative has produced a feasibility study[30] and a pilot project[31] using CCUS on a Stena Bulk medium range (MR) tanker. However, the OCGI's early conclusions are that capital and operating costs are a substantial hurdle, and other carbon reduction technologies (such as fuel switching, or using sails to reduce fuel needs) are likely to be more attractive in many circumstances.
Receiving, storage, regasification	**Low**	Because regasification emits relatively low emissions, it is not a strong candidate for CCUS. In addition, it is usually outside the zone of control of LNG proponents.

As noted above, the majority of emissions (75%) along the LNG lifecycle come from end-user combustion of the gas. Combustion can be an excellent fit for CCUS (depending on local geological conditions); however, it is generally outside the control of the LNG producer.

Another important factor to consider in terms of how CCUS fits with LNG is, as CCUS—like many large industrial undertakings—is not cheap. Costs can be minimized in several ways. One way is to include CCUS as part of a new build. CCUS used for capturing post-combustion emissions in new builds is about 80% cheaper than retrofitting existing facilities. A second way to minimize costs is to use CCUS to sequester carbon removed as part of the acid gas removal process or during reforming, which is less expensive than capturing CO_2 from the liquefaction process.[24]

Table 2: CCUS facilities that have natural gas processing as the emissions source

Project	Location	Operational date	Storage method	Annual carbon capture capacity (Mt CO_2)
Terrell Natural Gas Processing Plant	USA (Texas)	1972	Enhanced Oil Recovery	0.5
Shute Creek Gas Processing Plant	USA (Wyoming)	1986	Enhanced Oil Recovery	7
MOL Szank Field CO_2 EOR	Hungary	1992	Enhanced Oil Recovery	0.2
Sleipner CO_2 Storage	Norway	1996	Geological Storage	1
Core Energy CO_2-EOR	USA (Michigan)	2003	Enhanced Oil Recovery	0.35
In Salah CO_2 Storage	Algeria	2004	Geological Storage	1.1
Snohvit CO_2 Storage	Norway	2008	Geological Storage	0.7
Century Plant	USA (Texas)	2010	Enhanced Oil Recovery	5
Petrobas Santos Basin Pre-Salt Oil Field CCS	Brazil	2011	Enhanced Oil Recovery	7
Lost Cabin Gas Plant	USA (Wyoming)	2013 – Operation Suspended	Enhanced Oil Recovery	0.9
Uthmaniya CO_2-EOR Demonstration	Saudi Arabia	2015	Enhanced Oil Recovery	0.8
CNPC Jilin Oil Field CO_2 EOR	China	2018	Enhanced Oil Recovery	0.6
Gorgon Carbon Dioxide Injection	Australia	2019	Geological Storage	4
Qatar LNG CCS	Qatar	2019	Geological Storage	2.2
Glacier Gas Plant MCCS	Canada (Alberta)	2022	Geological Storage	0.2
CNOOC South China Sea Offshore CCS	China	2023	Enhanced Oil Recovery	0.3
Santos Cooper Basin CCS Project	Australia	2023	Geological Storage	1.7
Northern Delaware Basin CCS	USA (New Mexico)	2023	Geological Storage	0.03
North Field East Project (NFE) CCS	Qatar	2025	Under Evaluation	1
Abu Dhabi CCS Phase 2: Natural Gas Processing Plant	United Arab Emirates	2025	Enhanced Oil Recovery	2.3
Ghasha Concession Fields	United Arab Emirates	2025	Geological Storage	
PTTEP Arthit CCS	Thailand	2026	Geological Storage	1
Bayu-Undan CCS	Timor-Leste	2027	Geological Storage	10
Petronas Kasawari Gas Field Development Project	Malaysia	2023	Under Evaluation	
NextDecade Rio Grande LNG CCS	USA (Texas)	2025	Under Evaluation	5.5
South East Australia Carbon Capture Hub	Australia	2025	Geological Storage	2
Repsol Sakakemang Carbon Capture and Injection	Indonesia	2026	Geological Storage	2
Inpex CCS Project Darwin	Australia	2026	Geological Storage	7
Lang Lebah	Malaysia	2026	Geological Storage	
Otway Natural Gas Plant	Australia	2026	Geological Storage	0.2
G2 Net-Zero LNG	USA (Louisiana)	2027	Under Evaluation	4
Novatek Yamal	Russia	Late 2020s	Geological Storage	
Sempra Energy Hackberry CCS Project	USA (Louisiana)	Under Evaluation	Under Evaluation	
Grand Forks Blue Ammonia Capture Plant	USA (North Dakota)	Under Evaluation	Geological Storage	0.5

Source: Derived from the Global CCS Institute Facilities Database as of March 24, 2023

7.0 How Government Policy Can Support the Adoption of CCUS

CCUS projects are not only complex—they are also expensive to build.[6] A sample of projects in the U.S., Canada and Norway had construction costs that were in the range of US $0.5-1.6 billion.*

There are, however, two pieces of good news.

The first is that **costs are coming down**. In part, this is due to the learning curve from early projects such as the Quest CCS project in Alberta, Canada. Quest's owners have stated that if the project were to be built again, costs would be about 30% lower.[32] Recent studies show that next generation CCUS technology will be significantly cheaper and more efficient.[33] Costs are also reduced through the use of shared infrastructure models—like the hubs described above—that can achieve economies of scale.

The second piece of good news is that **governments recognize the high cost of early technology deployment** and many national or sub-national governments provide incentives—direct or indirect—to support the financial value proposition for CCUS deployment. The policy instruments that governments can use to encourage CCUS adoption are described below, along with some examples from different countries.

→ Government policies that provide direct financial support to CCUS projects

CCUS is expensive in all its stages: research and development, commercialization, construction and operations. Many governments provide direct financial support to bring down costs and make the capital investment competitive. However, different governments take different approaches. For example, the U.S. approach relies heavily on a tax credit, whereas the E.U. focuses more on grants and loans.[34] Some examples include:

- The Norwegian government has provided the equivalent of US $1.6 billion for the Longship CCS project, including ten years of operating support.[35] This represents about two-thirds of the project cost.

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* Snohvit (Norway): $0.5 BN; Quest (Canada): $1 BN; Petra Nova (USA): $1 BN; Century Plant Gas Processing (USA): $1.1 BN; Boundary Dam (Canada): $1.3 BN; Northern Lights/Longship (Norway): $1.6 BN

- In Canada, the federal government’s 2021 budget allocated $319 million to support CCUS research, development and demonstration projects.
- Australia’s CCUS Hubs and Technologies Program allocated AUD $250 million to deploy CCUS storage at scale, providing grants from $1 million to $30 million for businesses involved with CCUS.
- The U.S. tax credit known as “45Q” provides a tax credit for each ton of CO_2 stored. The credit sits at US $85/ton for CO_2 in geologic storage, and $60/ton if it is used for EOR or other industrial uses. The credit increases for direct air capture (DAC) projects: $180/ton for geologic storage and $130/ton for industrial uses.

Government policies that indirectly support CCUS financial viability

Government policies can also support conditions for CCUS projects to produce economic returns—enabling the sequestration of carbon to generate revenue rather than just act as a cost.

- Carbon offset markets enable CCUS projects to generate credits that have a monetary value and that can be traded or sold. Carbon offset markets currently exist in Australia, Canada, China, Columbia, Chile, Germany, Japan, Jordan, Kazakhstan, Mexico, New Zealand, South Korea, Switzerland, the U.K. and the U.S. These offset markets allow companies that produce emissions to reach their “net zero” goals by purchasing credits from companies that have successfully reduced their CO_2 output. Governments are often involved in developing the rules around what sorts of emissions reductions can be traded (and whether CCUS counts); and may also be involved in supporting a minimum price for credits.
- “Blue” hydrogen is produced from natural gas with CO_2 emissions sequestered through the use of CCUS. When governments support the development of blue hydrogen, they also support the development of CCUS facilities.

Government policies that restrict or price carbon emissions

The economics of CCUS improve when the government has restricted or placed a cost on industrial emissions of CO_2. If an emissions limit is set, CCUS can be used to achieve compliance with the limit and avoid penalties. If emissions are taxes or priced (i.e., a carbon tax), then the costs of CCUS can be balanced against the costs of paying the tax. Some examples of policies that price or constrain carbon emissions are:

- Canada’s carbon tax on large industrial emitters. The federal Output-Based Pricing System Regulations (OBPS) currently price industrial emissions at $65/tonne and will reach $170/tonne by 2030.
- The U.K.’s Emission Trading Scheme (ETS), a cap-and-trade system that restricts emissions from a range of energy intensive industries.

→ Government regulation of subsurface geology

Sequestering carbon underground requires drilling and access to “pore space” or the spaces between particles of rock deep under the surface. There can be complex legal questions over property rights and who owns or may access pore space. Governments can help CCUS adoption by developing a legal framework, proactively settling questions around property rights and training regulators to understand these complexities. Often this is done at a sub-national level, similar to the regulation of oil and gas development.

- In the United States, the ownership of pore space has been decided in some states (Wyoming, North Dakota, Montana and Nebraska) but not been definitively settled for most locations, including states such as Texas that would like to be active in CCUS.[36]
- The province of Alberta, Canada, and the state of Victoria, Australia, have designated the provincial/state government as the owner of all underground geological storage formations

The take-away message is that governments can use a range of direct and indirect policy approaches to help CCUS adoption. Given that CCUS is expensive, this support will likely be needed in almost all cases to make CCUS viable for LNG projects.

8.0 Alternatives to CCUS

Finally, it is important to note that CCUS is not the only way to reduce emissions from LNG production. Other alternatives exist—in particular, electrification, the use of hydrogen fuel and energy efficiency measures.

Electrification

Using electric motors to drive the liquefaction process is an excellent option for reducing emissions, and can result in the avoidance of up to 68% of CO_2 emissions compared to normal processes.[37] However, to substantially reduce emissions, local electrical grids must use a non-emitting source such as solar, wind, hydro or nuclear power.

Canada's LNG facilities have gone in this direction. Existing and approved LNG plants in British Columbia—LNG Canada, Woodfibre LNG and Cedar LNG—plan to be powered by renewable electricity from B.C.'s grid, which is almost entirely hydropower. The infrastructure to deliver this electricity is still under construction; gas turbines will be used until it is ready. In the United States, Freeport LNG in Texas is using entirely electrified motors to drive liquefaction compressors. Freeport LNG claims a 90% reduction in site combustion emissions, as well as a net production increase of 6.5% and reduced performance loss.[38]

Hydrogen

Hydrogen fuel is also being considered as a lower-emitting way to power LNG production, although no facilities using this technology appear to be up and running yet. As noted earlier in this report, pre-combustion processing of natural gas results in the production of hydrogen as a by-product. This hydrogen can be used to supplement the gas currently used in turbines.[37,39] In addition, some companies are looking at ways to use hydrogen fuel—which may be sourced from providers external to the LNG supply chain—to power liquefaction processes instead of gas.[40]

Energy efficiency

As a final note, different liquefaction technologies have different levels of energy efficiency. Some liquefaction processes, such as AP-C3MR or AP-DMR, can produce more LNG for the same gas turbine power. Similarly, aeroderivative gas turbines can be used in place of industrial gas turbines, resulting in higher simple cycle efficiencies and a reduction of around 14% of emissions compared with typical gas turbines. Combined cycle gas turbines can also improve power efficiency and reduce fuel use, as well as reducing CO_2 emissions by around 25% compared to a simple-cycle arrangement.[29] All of these technologies result in lower CO_2 emissions; their suitability of these technologies is often balanced against land use requirements, plant scale, complexity and cost.[37,41]

9.0 Conclusion

CCUS is a technology that has been demonstrated to be safe, effective and scalable. Examples from around the world show how it can be integrated with different industrial processes to reduce CO_2 emissions.

Parts of the LNG lifecycle are particularly well-suited for CCUS. About two-thirds of all existing CCUS facilities are applied to natural gas processing, as CO_2 must be removed before liquefaction can take place. Liquefaction also has high CCUS use potential, as emissions are high and concentrated in one place.

However, substantial challenges exist—both technical and financial. As a result, the suitability of CCUS compared to other decarbonization options (such as electrification or fuel switching) depends greatly on specific circumstances that are shaped by geography, government policy and local industrial context.

The LNG industry faces immense pressure to reduce emissions quickly and massively. As a proven technology that can be easily integrated into LNG processes, producers should strongly consider CCUS as part of a suite of solutions to achieve decarbonization goals.

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