GLOBAL STATUS OF CCS 2020

GLOBAL CCS INSTITUTE

CCS. VITAL TO ACHIEVE NET-ZERO

CCS.

VITAL TO ACHIEVE

NET-ZERO

1.0

INTRODUCTION

ABOUT US

The Global CCS Institute (the Institute) is an international think tank whose mission is to accelerate the deployment of carbon capture and storage (CCS), a vital technology to tackle climate change.

As a team of over 30 professionals, working with and on behalf of our Members, we drive the adoption of CCS as quickly and cost effectively as possible; sharing expertise, building capacity and providing advice and support so CCS can play its part in reducing greenhouse gas emissions.

Our diverse international membership includes governments, global corporations, private companies, research bodies and non-governmental organisations; all committed to CCS as an integral part of a net-zero emissions future.

The Institute is headquartered in Melbourne, Australia with offices in Washington DC, Brussels, Beijing, London and Tokyo.

ABOUT THE REPORT

CCS is an emissions reduction technology critical to meeting global climate targets. The Global Status of CCS 2020 documents important milestones for CCS over the past 12 months, its status across the world and the key opportunities and challenges it faces.

We hope this report will be read and used by governments, policy-makers, academics, media commentators and the millions of people who care about our climate.

AUTHORS

This report and its underlying analyses were led by Brad Page, Guloren Turan and Alex Zapantis. The team included Jamie Burrows, Chris Consoli, Jeff Erikson, Ian Havercroft, David Kearns, Harry Liu, Dominic Rassool, Eve Tamme, Alex Townsend and Tony Zhang.

ACRONYMS

BECCS Bioenergy with CCS
CCS Carbon Capture and Storage
CCUS Carbon Capture Utilisation and Storage
COP Conference of the Parties
DAC Direct Air Capture
DACCS Direct Air Capture with Carbon Storage
EC European Commission
EOR Enhanced Oil Recovery
ESG Environmental, Social and Corporate Governance
EU European Union
FEED Front-End Engineering Design
GHG Greenhouse Gas
Gt Gigatonne
GW Gigawatt
IPCC Intergovernmental Panel on Climate Change
LCFS Low Carbon Fuel Standard
MMV Monitoring, Measurement and Verification
Mt Million Metric Tonnes
MW Megawatt
NDC Nationally Determined Contribution
R&D Research and Development
SDS Sustainable Development Scenario
SMR Steam Methane Reformation
SOE State Owned Enterprise
TWH Terrawatt Hour
UNFCCC United Nations Framework Convention on Climate Change
UK United Kingdom
US United States of America
US DOE United States Department of Energy

BRAD PAGE

CEO,
Global CCS Institute

2020 will long be remembered as a most challenging year with the emergence and spread of the COVID-19 pandemic. The human toll has been awful. The economic impact will take decades to overcome. This has been a classic black swan event, not foreseen but with its arrival inflicting health, social, and economic damage on an exceptional scale. The world is still working through the management of the pandemic and with a vaccine not yet available, the need to learn to live in a world where COVID-19 is a reality, is fast presenting as the key challenge for governments, business and communities.

As many have observed, with governments needing to devise and implement economic stimulus packages to lift their nations out of recession and get people back to work, we have a once-in-a-generation opportunity to alter course and re-grow the global economy in a climate friendly and environmentally sustainable manner. Right now, we have before us an opportunity to embrace and accelerate the energy transition to deliver the new, clean energy and clean industry jobs that will sustain economies for many decades to come.

There is evidence that both the private and public sectors are increasingly choosing the road to climate friendly policies and investments. A growing list of countries have committed to net-zero emissions around mid-century. Alongside national government commitments, it has been remarkable to see in 2020 that despite difficult trading conditions, major multinational energy companies have made pledges to achieve carbon neutral outcomes by mid-century. For some this includes scope 3 emissions; those that are the result of the consumption (often combustion) of their products by customers. It has also been notable that significant Governments have included increased abatement ambition in their fiscal packages and that CCS has featured in several instances. This is welcomed and necessary. It has been clear for some time that achieving net-zero emissions around mid-century and containing temperature increases to well below 2°C will require the rapid deployment of all available abatement technologies as well as the early retirement of some emission intensive facilities and the retro-fitting of others with technology like CCS. It is also clear that Carbon Dioxide Removal (CDR) will be required at large scale as overshooting carbon budgets is, regrettably, almost assured.

The findings of this year's Global Status of CCS Report are consistent with these developments. As we have been reporting for the past 2 years, the pipeline of operating and in-development CCS facilities around the world is again growing. This year continues the upward trajectory. The diversity of the industries and processes to which CCS is being applied is a continued testament to the flexibility of CCS to remove emissions from industries that are hard to decarbonise but which manufacture products that will continue to be essential to daily life around the world.

The sustained lift in activity around CCS and the increased investment in new facilities is exciting and encouraging. But there is so much more work to do.

Just considering the role for CCS implicit in the IPCC 1.5 Special Report, somewhere between 350 and 1200 gigatonnes of CO_2 will need to be captured and stored this century. Currently, some 40 megatonnes of CO_2 are captured and stored annually. This must increase at least 100-fold by 2050 to meet the scenarios laid out by the IPCC. Clearly, a substantial increase in policy activity and private sector commitment is necessary to facilitate the massive capital investment required to build enough facilities capable of delivering these volumes.

As this year's report describes, in every part of the CCS value chain, substantial progress is being made. New, more efficient and lower cost capture technologies across a range of applications are changing the outlook for one of the most significant cost components of the CCS value chain. Proponents of the CCS hub model continue their impressive march towards reality and notable in this area is the move into operation of the Alberta Carbon Trunk Line. Carbon Dioxide Removal technologies are also featuring in increasing investment and project activity, while new and favourable policy settings in many countries, including the USA, UK, EU, and Australia are boosting the number of projects under active investigation and development.

It has been especially significant to see the increasing engagement with, and interest from, the financial and ESG sectors. Significant investment opportunities are being comprehended while the need for many businesses to transition to the future net-zero emissions world means that ESG advisers are looking to technologies that can deliver the necessary change.

The road ahead is challenging but CCS is increasingly well placed to make its significant and necessary contribution to achieving net-zero emissions around mid-century.

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LORD NICHOLAS STERN

IG Patel Professor of Economics & Government,
London School of Economics
Chair, Grantham Research Institute

In this year of unforeseen challenge and turmoil, the threat of climate change and the urgent need to reduce emissions and stabilise global temperatures has continued, with action as urgent as ever. While the tragic and widespread impacts of the COVID-19 health crisis have caused monumental disruption, many believe it has delivered a moment in time that can lead to fundamental change. This moment could be a turning point in our fight against climate change. A moment in history when we recognise that where we have come from is fragile and dangerous, and in many ways, inequitable. A moment that could deliver the impetus to strengthen commitments to emissions reduction and set us on not only a path to recovery, but to transformation and a new, sustainable and much more attractive form of growth and development.

If we are to have any chance of stabilising our global temperature, we must stabilise concentrations and that means net-zero greenhouse gas emissions. The lower the emissions, and the faster we can achieve net-zero, the lower the temperature at which we can stabilise. We have already learnt that we must aim to stabilise at 1.5 degrees – any higher and we threaten our way of life. Higher again, the impacts become almost unthinkable.

In recent years, both climate change language and action have moved toward this vital goal of net-zero, and right alongside it has been the need for carbon capture utilisation and storage, or CCUS. We have long known that CCUS will be an essential technology for emissions reduction; its deployment across a wide range of sectors of the economy must now be accelerated. Low-carbon technologies, including renewables and CCUS, point toward a viable pathway for achieving net-zero GHG emissions by 2050, even in sectors that were considered “too difficult” to decarbonise just a few years ago, such as steel, cement, aviation, and long-distance transportation.

Alongside this, our knowledge and understanding of climate change has, continued to improve, and its great pace and immense dangers are becoming ever more clear. Critically, we now know we must achieve net-zero emissions by mid-century, and we can see much of what we must do to achieve this. However, even armed with great insight and improved knowledge we have been slow as a world community in taking action to reduce our emissions.

Now, we must act with urgency. We must ensure that we do not return to the ‘old normal’ after the COVID-19 crisis. We are seeing the dangers of the pandemic, and we have seen the dangers of the fragile social fabric across the world which arose in part from the slow recovery and inequities of the last decade. And towering over all that are the dangers of unmanaged climate change.

We must alter the alarming path we are on and move swiftly to tackle climate change. We have, at the ready, strong techniques developed, both in the form of policy and technology, which can be implemented quickly, if we commit, and can make a major and vital contribution to achieving net-zero. It is time to go to scale. By applying what we know, and learning along the way, we can build the path to the zero-carbon economy that is crucial for the prosperity of this and future generations.

BY APPLYING WHAT WE KNOW, AND LEARNING ALONG THE WAY, WE CAN BUILD THE PATH TO THE ZERO-CARBON ECONOMY THAT IS CRUCIAL FOR THE PROSPERITY OF THIS AND FUTURE GENERATIONS.

Lord Nicholas Stern,
IG Patel Professor of Economics & Government,
London School of Economics
Chair, Grantham Research Institute

JADE HAMEISTER OAM

Polar explorer

- Youngest person to ski to the North Pole (age 14)
- Youngest woman to complete the 550km traverse of the Greenland icecap (age 15)
- Youngest person to ski from coast of Antarctica to South Pole (age 16)
- One of only three women in history to ski a new route to South Pole
- Australian Geographic Society Young Adventurer of the Year 2016 and 2018
- Order of Australia Medal (age 18) for service to polar exploration

All Jade's polar expeditions were unsupported and unassisted.

As the world battles the current global pandemic, another much greater challenge remains on course to alter life as we know it.

In 2020, climate change has been easily forgotten, but it has not gone away. Nor has the urgent need to address rising emissions, meet Paris agreement targets and achieve net-zero ambitions.

We have already seen the effects of climate change begin to take hold. Last Summer, in my home country of Australia, we experienced unprecedented and devastating fires, and throughout this year have seen coral bleaching on the Great Barrier Reef continue at a pace never before seen.

We must urgently begin to accept the challenge ahead of us and the need to respond to it. We must also reframe our attitude to global warming and see it as a catalyst for innovation to deliver growth and create a more sustainable and prosperous future for us all.

Recent net-zero commitments from organisations and nations around the world bring hope that the challenge is being accepted; but what matters most is action. Commitments are nothing without real action to create real change.

At 19, I am no expert on the science of global warming, nor am I am expert on how to convene world leaders to act and combat the greatest threat we have ever known.

But I am likely the only person on the planet of my generation to have the privilege of first-hand experience in our three main polar regions; journeys that saw me cover a total of around 1,300km in 80 days.

My polar expeditions confirmed for me that global warming is an undeniable truth. I saw the effects to our Earth in some of our most beautiful and fragile environments.

These journeys changed me forever and I now feel a deep emotional connection with our mother Earth and a strong sense of responsibility to play my part in its protection.

We need to embrace all solutions available to us to reduce emissions and achieve the goal of net-zero by 2050 – and we need carbon capture and storage technologies.

There is no doubt we have the science, the knowledge and the solutions to save ourselves from the catastrophic consequences of climate change.

Now, we need massive and urgent action.

> **WE NEED TO EMBRACE ALL SOLUTIONS AVAILABLE TO US TO REDUCE EMISSIONS AND ACHIEVE THE GOAL OF NET-ZERO BY 2050 – AND WE NEED CARBON CAPTURE AND STORAGE TECHNOLOGIES.**

Jade Hameister OAM,
Polar explorer

THE NEED FOR CCS

2.0 THE NEED FOR CCS

In the fight against climate change, carbon capture and storage (CCS) is a game-changer. Its ability to avoid carbon dioxide (CO_2) emissions at their source and enable large-scale decreases to CO_2 already in the atmosphere via CO_2 removal technologies, make it an essential part of the solution.

To avoid the worst outcomes from climate change, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 degrees Celsius[1] highlighted the importance of reaching net-zero emissions by mid-century. It presents four scenarios for limiting global temperature rise to 1.5 degrees Celsius – all require CO_2 removal and three involve major use of CCS (see Figure 1). The scenario that does not utilise CCS requires the most radical changes in human behaviour.

To achieve cost-effective net-zero emissions, CCS investment can help in four main ways:

- **Achieving deep decarbonisation in hard-to-abate industry**
  The cement, iron and steel, and chemical sectors emit carbon due to the nature of their industrial processes, and high-temperature heat requirements. They are among the hardest to decarbonise.Several reports, including from the Energy Transition Commission and International Energy Agency (IEA) conclude that achieving net-zero emissions in hard-to-abate industries like these may be impossible and, at best, more expensive without CCS. CCS is one of the most mature and cost-effective options.

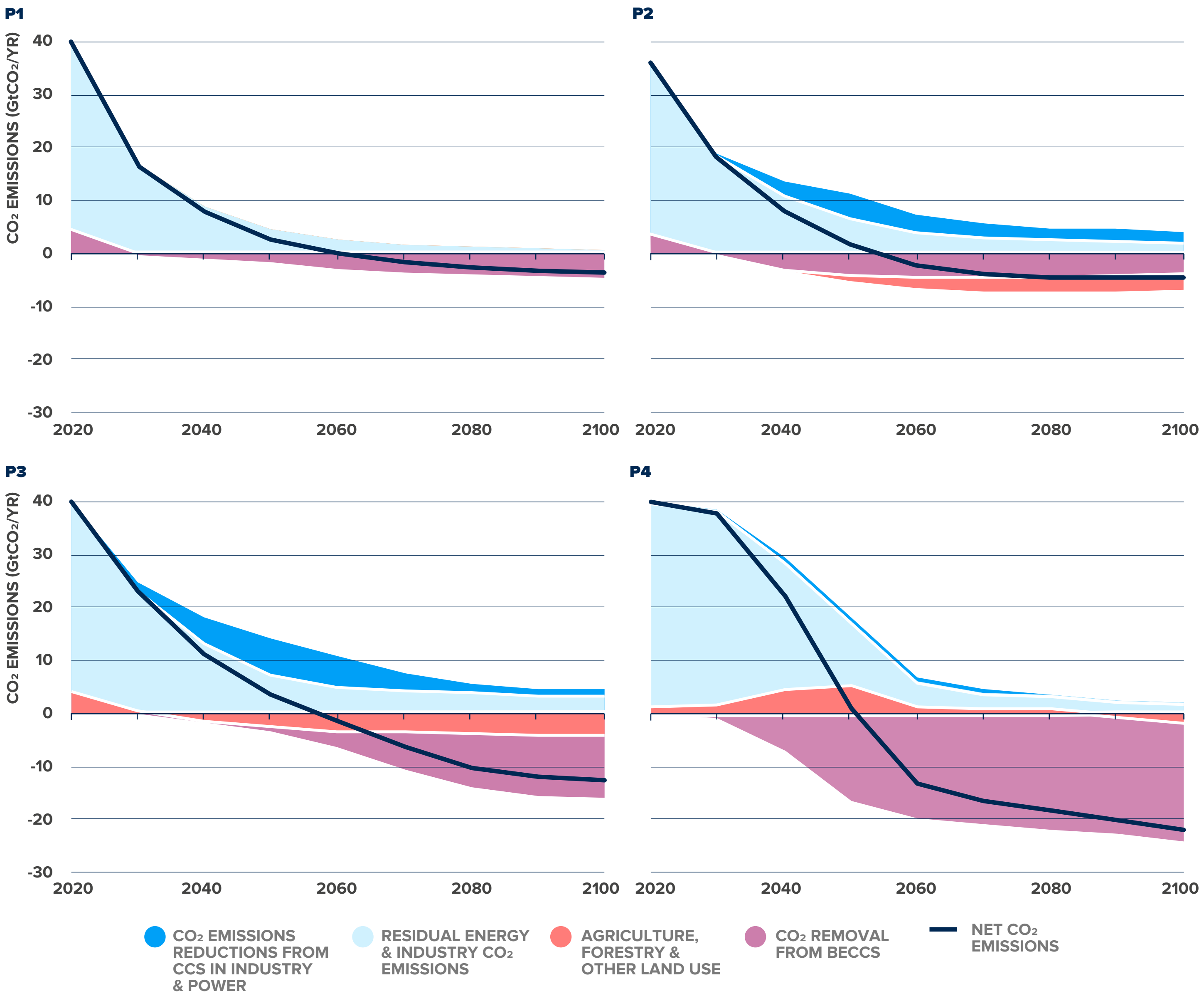


FIGURE 1 ILLUSTRATIVE PATHWAYS IN THE IPCC SPECIAL REPORT ON 1.5 DEGREES CELSIUS[a]

- **Enabling the production of low-carbon hydrogen at scale**
  Hydrogen is likely to play a major role in decarbonising hard-to-abate sectors. It may also be an important source of energy for residential heating and flexible power generation. Coal or natural gas with CCS is the cheapest way to produce low-carbon hydrogen. It will remain the lowest cost option in regions where large amounts of affordable renewable electricity for hydrogen producing electrolysis is not available and fossil fuel prices are low. To decarbonise hard-to-abate sectors and reach net-zero emissions, global hydrogen production must grow significantly, from 70 Mt per annum (Mtpa) today[i] to 425–650 Mt a year by mid-century.
- **Providing low carbon dispatchable power**
  Decarbonising power generation is crucial to achieving net-zero emissions. CCS equipped power plants supply dispatchable and low-carbon electricity, as well as grid-stabilising services, such as inertia, frequency control and voltage control. Grid-stabilising services cannot be provided by solar photovoltaics (PV) or wind generation. CCS complements renewables, helping make the low-carbon grid of the future resilient and reliable.
- **Delivering negative emissions**
  Residual emissions in hard-to-abate sectors need to be compensated for. CCS provides the foundation for technology-based carbon dioxide removal, including bioenergy with CCS (BECCS) and direct air capture with carbon storage (DACCS). While carbon dioxide removal is not a silver bullet, every year that passes without significant reductions in CO_2 emissions, makes it more necessary.

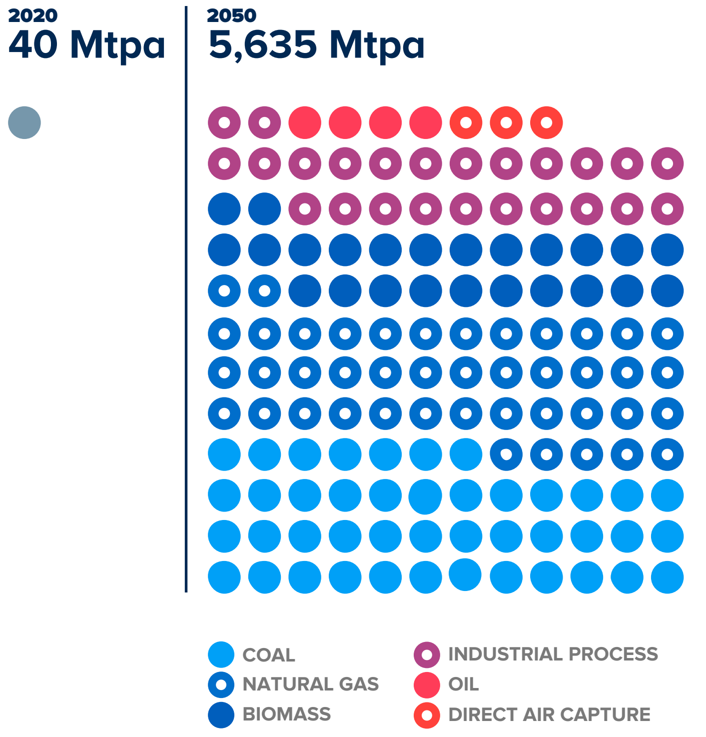


FIGURE 2 CO_2 CAPTURE CAPACITY IN 2020 AND 2050 BY FUEL AND SECTOR IN THE IEA SUSTAINABLE DEVELOPMENT SCENARIO[b]

Includes CO_2 captured for use (369 Mtpa) and storage (5,266 Mtpa) in 2050

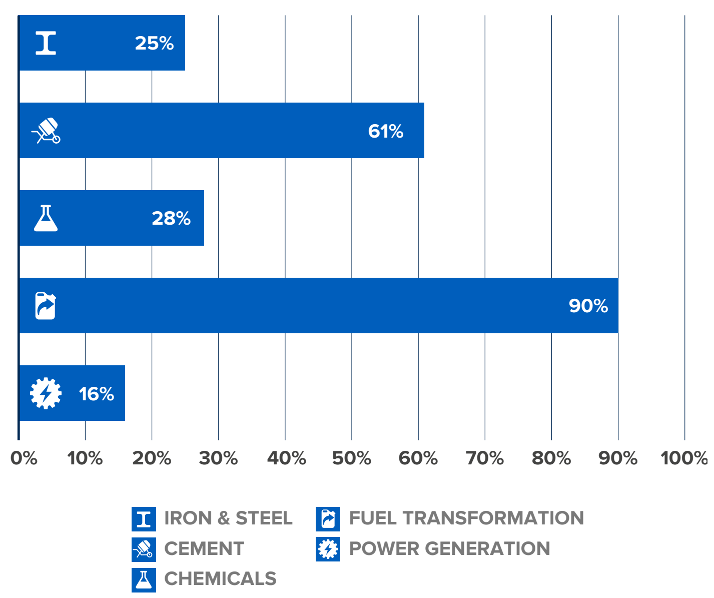


FIGURE 3 CONTRIBUTION OF CCUS TO SECTOR CO_2 EMISSIONS REDUCTIONS UP TO 2070 IN THE IEA SUSTAINABLE DEVELOPMENT SCENARIO[c]

Fuel transformation covers sectors such as refining, biofuels, and merchant hydrogen and ammonia production

The IEA's Sustainable Development Scenario (SDS)[2] describes a future where the United Nations (UN) energy related sustainable development goals for emissions, energy access and air quality are met. The mass of CO_2 captured using CCS goes up from around 40 Mt of CO_2 per annum today to around 5.6 gigatonnes (Gt) in 2050 – a more than hundredfold increase (Figure 2). Its contribution is significant, accounting for between 16 per cent and 90 per cent of emissions reductions in the iron and steel, cement, chemicals, fuel transformation and power generation sectors (Figure 3). The versatility and strategic importance of CCS in a net-zero emissions future is clear.

Vital for reducing CO_2 emissions, investment in CCS also provides several economic benefits:

- Creating and sustaining high-value jobs
- Supporting economic growth through new net-zero industries and innovation
- Enabling infrastructure re-use and the deferral of shut-down costs.

Critically, CCS also facilitates a 'just transition'[3]. One of the main challenges to achieving a just transition is that job losses from high emissions industries may be concentrated in one place, while low-carbon industry jobs are created somewhere else. Even where geography is not a barrier, it is rare that mass job losses are followed quickly by wide scale opportunities. CCS facilitates a just transition by allowing industries to make sustained contributions to local economies while moving toward net-zero.

Time is running out to reach net-zero emissions and limit temperature rise to 1.5 degrees (°C). Although the COVID-19 crisis has resulted in unprecedented reductions in energy demand and emissions, the long-term picture for CCS has not changed. To have the greatest chance of achieving net-zero emissions, it is essential that wide use of CCS happens quickly. Now is the time to accelerate investment in CCS.

3.0

GLOBAL STATUS OF CCS 2020

3.1 GLOBAL CCS FACILITIES UPDATE AND TRENDS

MATURING CCS INDUSTRY NEEDS UPDATED CLASSIFICATION SYSTEM

The Global CCS Institute has introduced an updated classification system in 2020 to better reflect the CCS industry's development. Prior to this *Global Status of CCS Report 2020*, we identified two categories of facilities, based on their annual CO_2 capture capacity:

1. Large-scale CCS facilities:
   - Facilities which capture CO_2 from industrial sources with a capacity of 400 ktpa or greater
   - Facilities which capture CO_2 from power generation with a capacity of 800 ktpa or greater
   - CO_2 transport infrastructure and storage hub projects with a capacity of 400 ktpa or greater.
2. Pilot and demonstration facilities:
   - Facilities which capture CO_2 from industrial sources or power generation, that do not meet large-scale CCS facility capacity thresholds.

The objective of the Institute, when the annual CO_2 capture category system was first created, was to develop facilities large enough to demonstrate CCS at a commercially relevant scale – big enough to apply the lessons of commercial deployment but without significant scale-up risk. Hence, the *highest* classification of CCS facility was called *large-scale*. Thresholds for qualification were set accordingly.

Over the past year or so, that classification system has become less useful. Since smaller capture facilities can be commercially viable – CCS hubs now offer economies of scale in transport and storage to multiple, smaller CO_2 sources – capture capacity is no longer the best way to classify facilities. Demonstrating new technologies remains as important as it is in any industry, but the primary objective now is to deploy commercially available, mature CCS technologies to meet ambitious climate targets.

NEW CCS FACILITIES CLASSIFICATION SYSTEM

From this Global Status of CCS Report 2020 onward, CCS facilities will be classified as:

1. Commercial CCS facilities:
   - CO_2 captured for permanent storage as part of an ongoing commercial operation
   - Storage may be undertaken by a third party or by the owner of the capture facility
   - Generally have economic lives similar to the host facility whose CO_2 they capture
   - Must support a commercial return while operating and/or meet a regulatory requirement.
2. Pilot and demonstration facilities:
   - CO_2 captured for testing, developing or demonstrating CCS technologies or processes
   - Captured CO_2 may or may not be permanently stored
   - Generally short life compared to large commercial facilities – determined by the time required to complete tests and development processes or achieve demonstration milestones
   - Not expected to support a commercial return during operation.

IMPACT OF THE INSTITUTE'S CLASSIFICATION SYSTEM

The new classification system has resulted in these changes:

- Six facilities formerly classified as pilot and demonstration now classified as commercial
- Brevik Norcem and Fortum Oslo Varme now two separate commercial CCS facilities (they were grouped as one large-scale facility, part of the Norway Full Chain Project)
- Occidental Petroleum Corporation and White Energy's Plainview and Hereford Ethanol enhanced oil recovery (EOR) facilities now classified as two separate commercial CCS facilities (were grouped as one)
- Six CO_2 transport and storage projects previously classified as large-scale CCS facilities will be listed separately in a new 'Hubs' section in our CO_2RE Database which is scheduled for construction in 2021. Until then, these hubs will be delineated from facilities by calling them 'CO_2 Storage'.

Any reference to new facilities or growth in the CCS pipeline refers exclusively to facilities that have been added to our database, not existing facilities that have been reclassified.

FACILITIES PIPELINE GROWTH IN 2020

Figure 4 shows the development of the commercial CCS facility pipeline over the past decade. Total capacity decreased year on year between 2011 and 2017, likely due to factors like the public and private sector focus on short term recovery after the global financial crisis. However, for the past three years, there has been strong growth.

One of the big factors driving CCS growth is recognition that achieving net-zero greenhouse gas (GHG) emissions is increasingly urgent. This was given effect with the 2015 Paris Agreement establishing a clear ambition to limit global warming to less than two degrees Celsius. Ambition has since strengthened to limiting warming to 1.5 degrees Celsius. This has refocused governments, the private sector and civil society on emissions reduction. Governments have enacted stronger climate policy and shareholders have applied greater pressure on companies to reduce their scope one, two and three emissions[ii]. Around 50 countries, states/provinces or cities, and hundreds of companies have now committed to achieving net-zero emissions by mid-century.

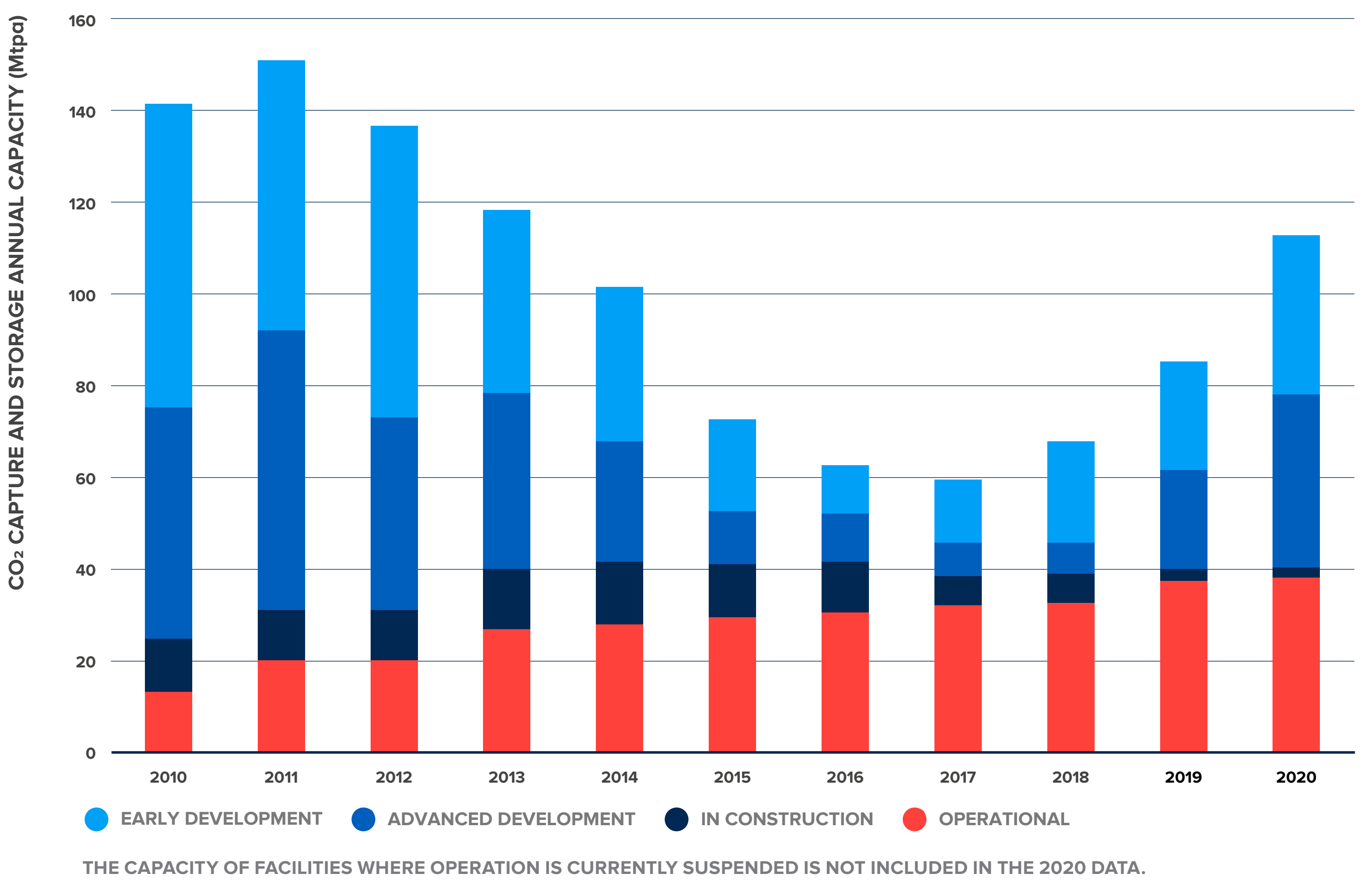


FIGURE 4 PIPELINE OF COMMERCIAL CCS FACILITIES FROM 2010 TO 2020: CCS CAPACITY[d]

There is a slow movement of capital away from higher to lower emission asset classes, as demonstrated by the rise of environment social governance (ESG) investment funds and green bonds, and decreasing availability of debt financing for coal-related investments. The need to address hard-to-abate sectors like steel, fertiliser, cement and transport has become more pressing and is less often postponed.

These global macro-trends have motivated a more thorough analysis of how to achieve net-zero emissions at the lowest possible risk and cost. It is reasonable to conclude that this can best be achieved when the broadest portfolio of technologies, including CCS, is available. Without CCS, net-zero is practically impossible.

One of the big factors driving CCS growth is recognition that achieving net-zero greenhouse gas emissions is increasingly urgent.

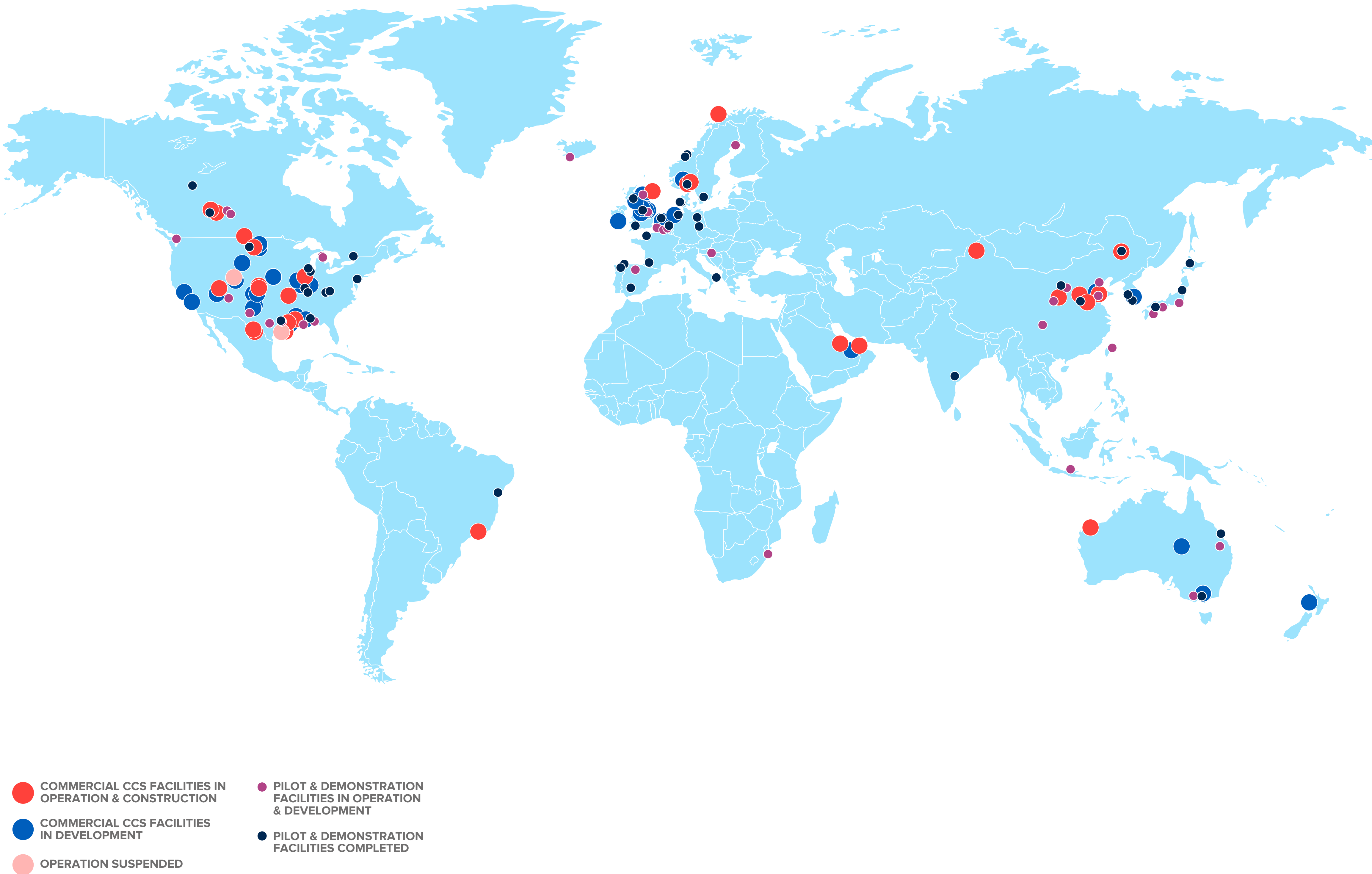


FIGURE 5 WORLD MAP OF CCS FACILITIES AT VARIOUS STAGES OF DEVELOPMENT[c]

Seventeen new commercial facilities entered the project pipeline since the Global Status of CCS Report 2019 was published. The United States (US) again leads the global league table, hosting 12 of the 17 facilities initiated in 2020. US success demonstrates convincingly that where policy creates a business case for investment, projects proceed. The other facilities are
in the United Kingdom (two), Australia and New Zealand.

Today, there are 65 commercial CCS facilities:[iii]

- 26 are operating
- Two have suspended operations – one due to the economic downturn, the other due to fire
- Three are under construction
- 13 are in advanced development reaching front end engineering design (FEED)
- 21 are in early development.

CCS facilities currently in operation can capture and permanently store around 40 Mt of CO_2 every year. There are another 34 pilot and demonstration-scale CCS facilities in operation or development and eight CCS technology test centres.

Three aspects of recent growth in the commercial CCS project pipeline are worth mentioning:

1. **Enhanced tax credit in the US**
   - US involvement in 12 of the 17 new facilities in 2020 is largely due to the enhanced 45Q tax credit signed into law in 2018, with the Internal Revenue Service issuing more detailed guidance in 2020.
   - Some US facilities will also benefit from the California low-carbon fuel standard (LCFS). Credits under this scheme were trading up to US $212 per tonne CO_2 in 2020.
2. **Hubs and clusters**
   - Hubs and clusters significantly reduce the unit cost of CO_2 storage through economies of scale and offer commercial synergies that reduce investment risk.
   - Most new US commercial facilities have the opportunity to access CarbonSAFE CO_2 storage hubs which are under development and supported by the US Department of Energy (US DOE)[4].
   - The two new commercial facilities in the United Kingdom (UK) are both associated with Zero Carbon Humber, which aims to be the UK's first net-zero industrial cluster.
3. **Hydrogen: Fuel of the future**
   - Coal gasification, or natural gas reforming with CCS, is the lowest cost option for producing commercial quantities of clean hydrogen. Jockeying for a chance to win market share in clean hydrogen supply is a significant factor in the growth of early-stage CCS project studies. Examples include Project Pouakai Hydrogen Production in New Zealand, the Hydrogen Energy Supply Chain project in Australia (pilot plant under construction) and the Hydrogen to Humber Saltend project – one of many large-scale hydrogen projects in development in the UK.

EXAMPLES OF NEW CCS FACILITY DEVELOPMENTS

Global progress in CCS over the past year has been substantial and there are too many new CCS facilities to mention here (see CO2RE, our Global CCS Facilities Database, for a comprehensive listing). Below are a just a few examples illustrating the broad applications, and spread, of CCS in 2020:

- The Drax BECCS project commenced in the UK. The existing Drax power station has already undergone modification, transforming from coal-fired to one firing biomass. The addition of CCS will further reduce its CO_2 footprint. Drax is targeting capture of four Mtpa of CO_2 from one of its four power generation units. Storage will be in the North Sea oil fields, with a proposed start date of 2027. This project is part of a larger program to eventually deploy CCS on all four of its bioenergy power units by the mid-2030s.
- Enchant Energy is developing a CCS project for its coal-fired San Juan Generating Station in New Mexico, USA. Up to six Mt of CO_2, captured through post-combustion capture technology per year, would be used for EOR in the Permian Basin.
- In Australia, energy company Santos announced it has commenced the FEED study for a CCS project to capture CO_2 from natural gas processing at its Moomba gas plant. The project will capture and geologically store 1.7 Mt of CO_2 in a nearby field, each year. Santos has claimed abatement costs of less than AUD $30 per tonne (US $22)[5].
- Lafarge Holcim is looking at the feasibility of carbon capture on its cement plant in Colorado, US. This project, in partnership with Svante, Oxy Low Carbon Ventures and Total, would capture 0.72 Mt of CO_2 per year. Using the captured CO_2 for EOR, it would receive 45Q tax credits and would be the largest-scale use of Svante adsorption-based capture technology ever.
- The ZEROS project involves the development of two innovative oxyfuel combustion waste-to-energy (WtE) (power) plants in Texas, USA with a capture target of 1.5 Mt of CO_2 per year. Oxyfuel combustion ensures a high concentration of CO_2 in its flue gas, making carbon capture more economical than in conventional WtE plants.
- The Pouakai project, owned by 8 Rivers Capital, is a hydrogen, fertiliser, and power generation industrial complex in the Taranaki Region, New Zealand. It will use natural gas as a feedstock and CCS (approx. 1 Mtpa CO_2), resulting in near-zero emissions. Project Pouakai will use one natural gas processing facility with three integrated processes:
  1. NET Power's Allam Cycle electricity generation
  2. 8 Rivers' 8RH2 hydrogen production technology
  3. Well-established commercial ammonia synthesis and synthetic nitrogen fertiliser production process technologies.

The project is progressing through studies with ambition for operations mid-decade.

Figure 6 plots all commercial facilities in operation, construction or advanced development by host industry, and actual or expected operational commencement year.

OPERATING FACILITY MILESTONES

Some of the most significant industry milestones reached in the past year are as follows:

The Alberta Carbon Trunk Line (ACTL) commenced operation in March 2020. With a capacity of 14.6 Mt of CO_2, this key infrastructure for Canadian industry transports CO_2 for EOR storage in Central Alberta[6]. It's the world's highest capacity CO_2 transport infrastructure and was developed with the future in mind. Its foundation CO_2 capture facilities are the Sturgeon oil refinery and Nutrien Fertiliser plant. Together these two commercial CCS facilities supply 1.6 Mt per year of CO_2, leaving ample additional capacity for future capture at industrial plants in Alberta.

The Gorgon Carbon Dioxide Injection facility on Barrow Island, Western Australia, was commissioned in August 2019 and has been storing CO_2 since. Chevron has progressively commissioned its CO_2 compression trains, ramping up CO_2 injection capacity. The milestone of one Mt of CO_2 stored was announced in February this year[7]. Gorgon is the largest dedicated geological storage operation in the world with a capacity of up to 4 Mtpa CO_2.

Air Products Steam Methane Reformer facility captures CO_2 from two steam methane reformers located in the Valero Energy refinery at Port Arthur, Texas. It produces 500 tonnes of clean hydrogen per day. In April 2020, the US DOE published that the facility had cumulatively captured and stored over six Mt of CO_2.

Quest CCS facility captures CO_2 from three steam methane reformers at the Scotford Upgrader in Alberta, Canada. It produces 900 tonnes of clean hydrogen per day. In July 2020, the facility reached five Mt of CO_2 safely and permanently stored in dedicated geological storage.

Petrobras Santos Basin Pre-Salt Oil Field CCS facility uses membranes to capture CO_2 from offshore natural gas processing and reinjects it into the Lula, Sapinhoá and Lapa oil fields for EOR. Membranes have size and weight advantages which make them best suited to offshore applications. Petrobras is the largest project using membrane technology globally. The project's capacity recently increased from three to 4.6 Mt per year[8].

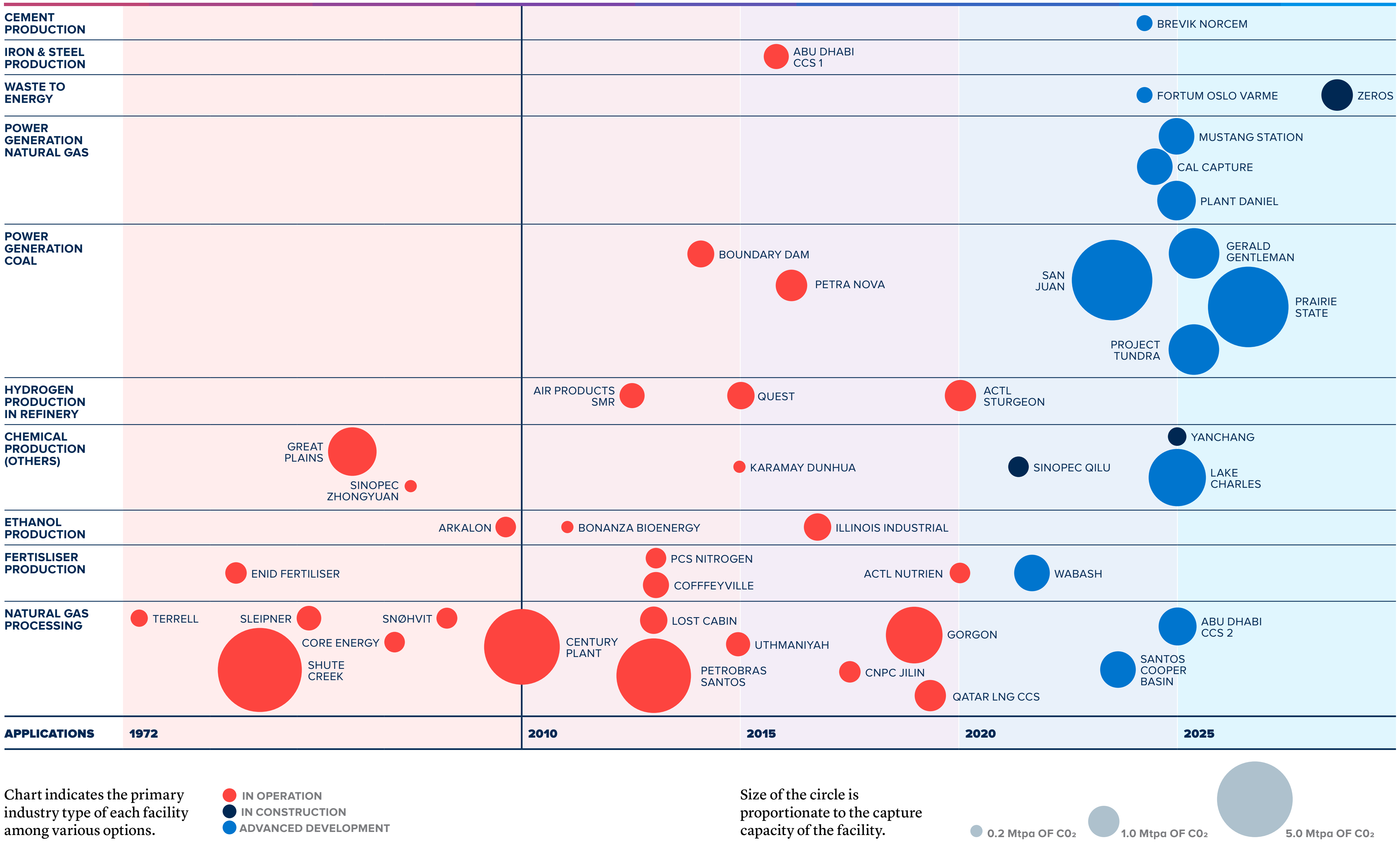


FIGURE 6 A PORTFOLIO OF COMMERCIAL CCS FACILITIES IN VARIOUS POWER AND INDUSTRIAL APPLICATIONS FACILITIES INCLUDE THOSE IN OPERATION, UNDER CONSTRUCTION AND IN ADVANCED DEVELOPMENT. AREA OF CIRCLES IS PROPORTIONAL TO CURRENT CCS CAPACITIES.[f]

HUBS AND CLUSTERS: MOVING TOWARD MORE FLEXIBLE CCS NETWORKS

Like most industries, CCS benefits from economies of scale. Larger scale compression, dehydration, pipeline and storage drives big reductions in cost per tonne of CO_2.

Early developments in CCS adopted a point-to-point model, which tended to favour situations where a single large emitter (e.g. a power station or gas processing plant) was situated within reasonable distance of a large storage site.

Hubs aggregate, compress, dehydrate and transport CO_2 streams from clusters of facilities. There are significant economies of scale to be obtained, particularly in the capital costs of compression plants (up to approximately 50 MW of power consumption), and in pipelines (up to around 10-15 Mtpa of capacity). This industrial ecosystem with multiple customers and suppliers of CCS services also helps reduce risk. Figure 7 below shows CCS hubs and clusters either operating, or progressing through studies, in 2019–20.

Hubs also enable better source/sink matching between carbon capture facilities and storage resources. They allow for more flexible compression operations, by allowing greater turndown (reduction in flow) than would be possible with individual compression plants at every source.

One of the most advanced hubs in development is the Northern Lights Project (see Figure 8). In the North Sea, this Norwegian CCS hub aggregates CO_2 streams, beginning with foundation sources from WtE and cement plants (combined capacity of 0.8 Mtpa of CO_2). Developed by Equinor, Shell and Total, the project will compress and liquefy CO_2 at source plants before transport by dedicated CO_2 ship, to a storage site[9]. The project is targeting a 2024 commissioning date.

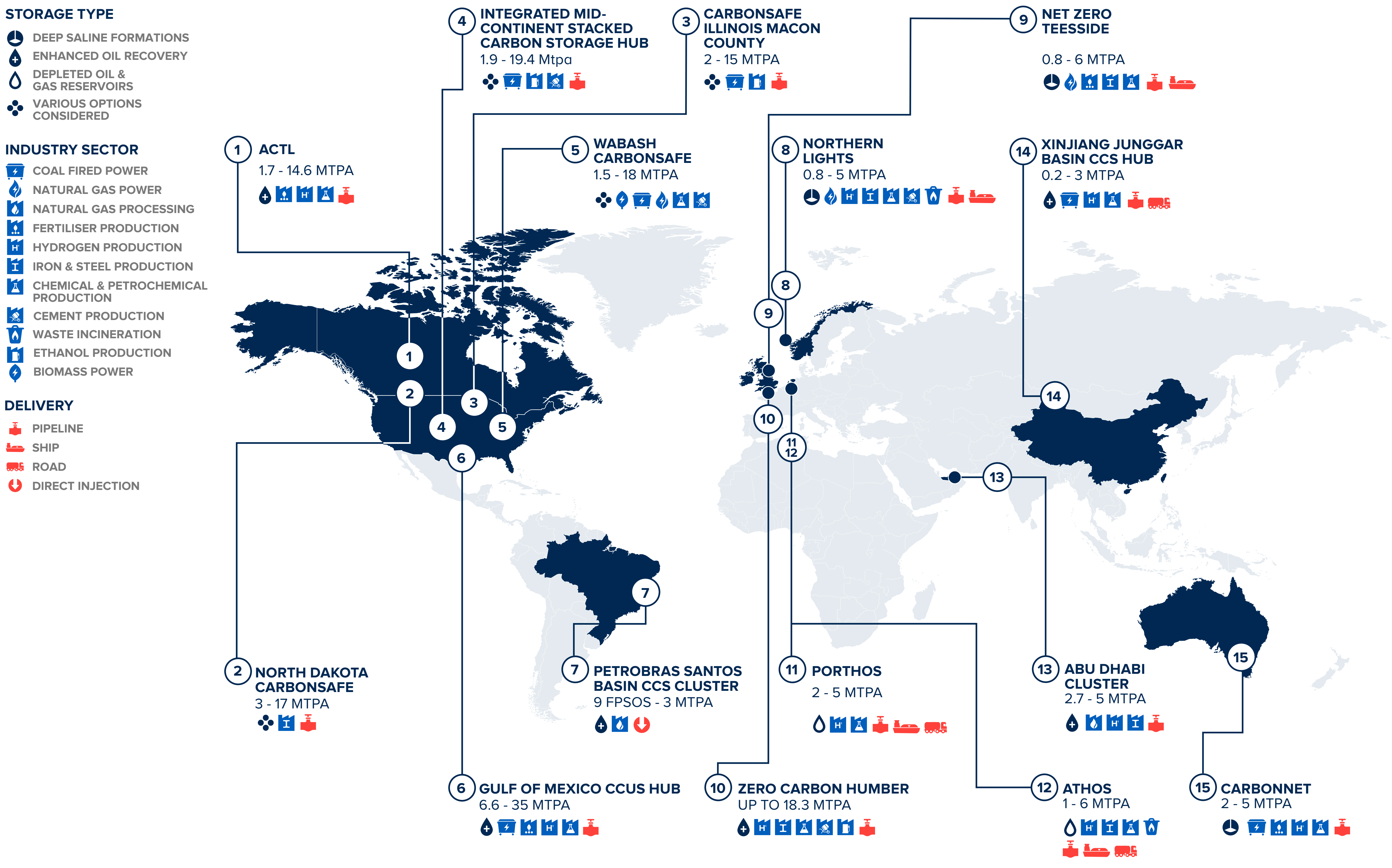


FIGURE 7 HUBS AND CLUSTERS OPERATING OR IN DEVELOPMENT[g]

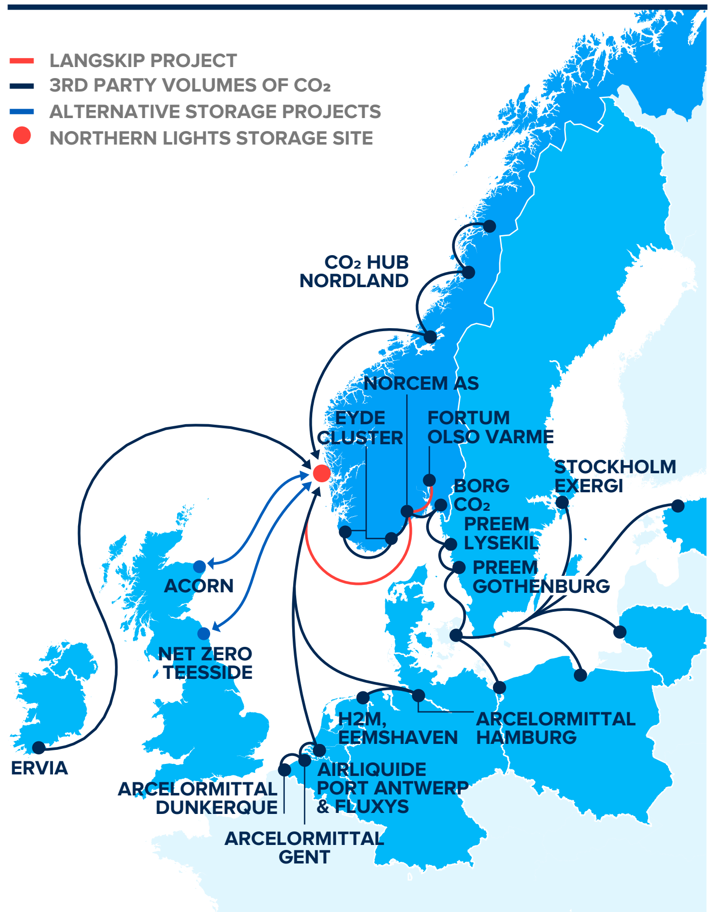


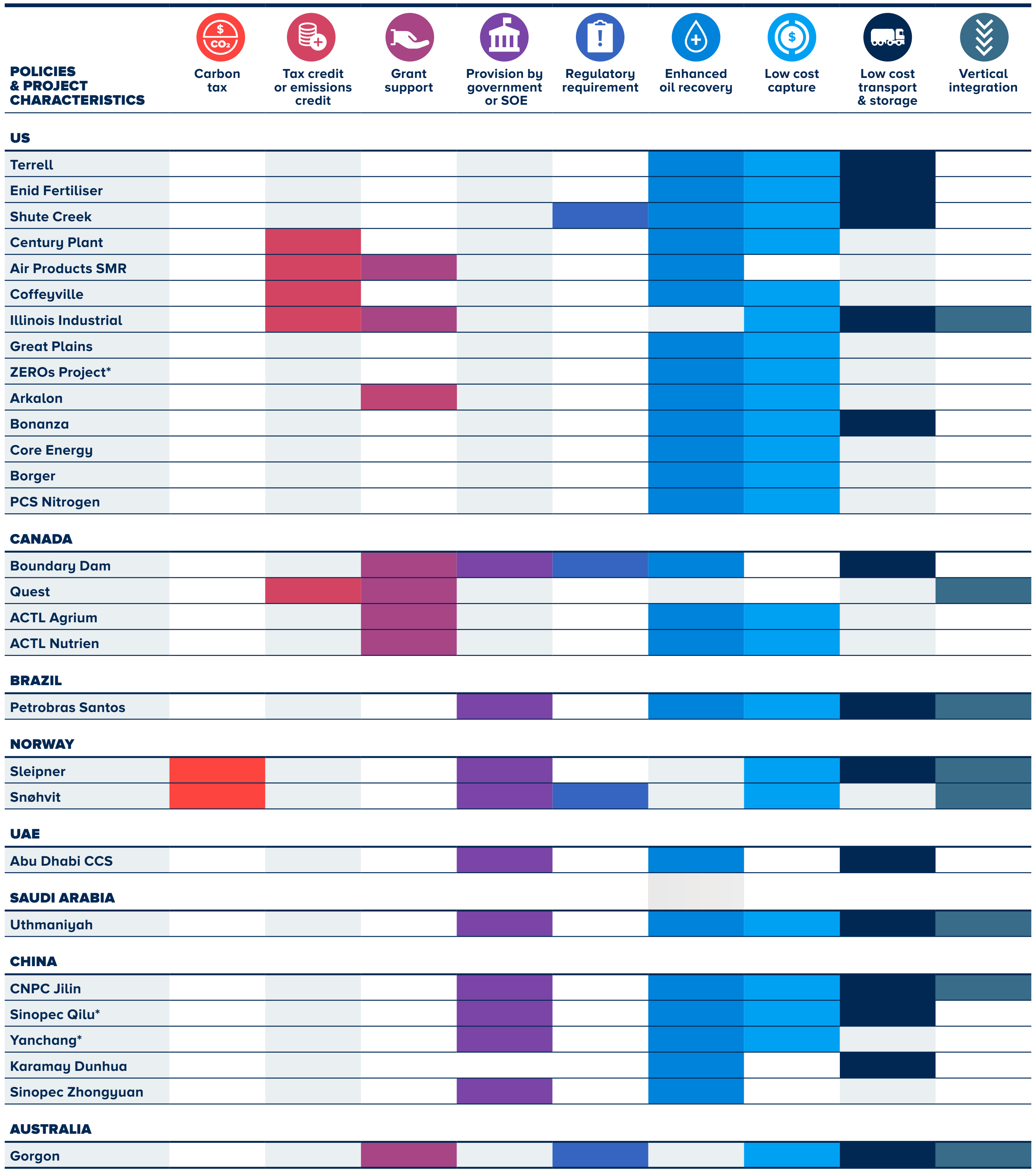
FIGURE 8 NORTHERN LIGHTS PROJECT – POTENTIAL SOURCES OF CO_2[h]

IMPACT OF COVID-19

While development and deployment of CCS gathered momentum in 2020, the sector is not immune to the economic downturn brought on by COVID-19. The epidemic severely impacted the global economy and entire industries significantly scaled back production. This includes the global oil sector which saw extraordinarily rapid falls in demand and price.

The Petra Nova CCS facility in Texas, US successfully captured CO_2 from the NRG-owned W.A. Parish power station from when it was commissioned in early 2017. Its business model, based on using CO_2 for EOR, was severely impaired by the oil price decline and, in March 2020, carbon capture operations paused. NRG indicated they should restart when economic conditions improve.

3.2 POLICY AND REGULATION



*In construction

FIGURE 9 THE MAIN POLICIES AND PROJECT CHARACTERISTICS THAT HAVE ENABLED LARGE-SCALE FACILITIES[i]

3.2.1 POLICY UPDATE

Estimates range about how much CO_2 must be captured and stored to achieve net-zero emissions. *The Special Report on Global Warming of 1.5 Degrees Celsius*[1] reviewed 90 scenarios and almost all required CCS to limit global warming to 1.5 degrees Celsius:

- Ninety percent required that global CO_2 storage reach 3.6 Gt per year or more by 2050
- Across all scenarios, the average mass of CO_2 permanently stored in 2050 was 10 Gt.

Today's worldwide installed capacity of CCS is around 40 Mtpa. To achieve net-zero emissions, it must increase more than a hundredfold by 2050. Stronger policy to incentivise rapid CCS investment is overdue. The current fleet of commercial CCS facilities provides examples of the mix of policies and project characteristics that have encouraged investment (see Figure 9).

Large-scale infrastructure projects are capital intensive. Typically, CCS design and construction costs are in the hundreds of millions, sometimes billions, of US dollars. Companies are most likely to invest where there is a large capital injection from government, through direct grant funding, to support private sector equity investments. State Owned Enterprises have also invested in CCS facilities.

With most of the world's liquidity locked inside the private sector, the challenge is to attract banks and institutions to invest in CCS projects. While most risks in CCS are general and can be mitigated over the course of a project, there are other risks that the private sector considers too great to accommodate. The risks emerge from several market failures:

- **Revenue risk due to an insufficient value on CO_2**

  While the sale of CO_2 for EOR has generated revenue for some CCS projects, large-scale deployment requires stronger climate policies. In most jurisdictions, the cost of capture, transportation and storage of CO_2 is greater than the value currently placed on it. The carbon price needed to cost effectively reduce emissions in line with the Paris Agreement is estimated at US $40-80/t$CO_2$ by 2020 and US $50-100/t$CO_2$ by 2030[10]. As much as 450 MtCO_2 could be captured, used and stored with a commercial incentive as low as US$40/t$CO_2$ by deploying CCS on the many low-cost opportunities available[11].

- **Interdependency or cross chain risk**

  CCS facilities may involve one source, one sink, and one pipeline. These disaggregated business models are expensive and there is an interdependency risk. For example, if the industrial source of CO_2 closes, the pipeline and storage operators both have no customers and no revenue.

- **Unlimited long-term storage liability risk**

  While the risk of leakage from a diligently selected storage resource is diminishingly small, it is not zero. If there are no limitations on liability, the storage operator is liable for any leakage at any time in the future. It is very difficult for private sector investors to accept such unlimited and perpetual liability, particularly in emerging industries like CCS where experience is limited.

Investors are unlikely to generously fund projects exposed to any of these risks. If they do, capital will be expensive. To achieve net-zero emissions, governments must implement policy frameworks that mitigate and manage risks, allocating them to organisations best placed to manage them at lowest cost. A summary of potential policy responses is provided in Table 1.

Governments will choose a policy framework that best suits its circumstances, and so long as a viable business case can be made, the private sector will invest in CCS. Like all technologies, CCS follows a learning curve whereby the cost of developing a CCS project will come down with deployment. This in turn reduces the cost of development, allowing smaller emitters to participate in investments. At the same time, risks are reduced with deployment through learning by doing, and this will lead to increased participation from financiers, including institutional investors.

BARRIER	EXAMPLES OF POTENTIAL POLICY RESPONSE
Insufficient value on CO_2 emissions	Introduce a value on CO_2 emissions reductions, for example through a carbon tax, tax credit, emissions trading scheme, CCS obligation, emissions performance standard or through government procurement standards. In doing so, this will enable investments in capture facilities which can then pass on part of the benefit to transportation and storage providers.
Interdependency of the CCS value chain	Provide capital support to enable the development of shared T&S networks, with a focus on integrated hubs and clusters where economies of scale can reduce unit costs and a diversified source of emissions can reduce the risk of asset stranding. Governments may initially own the T&S infrastructure. As more emitters connect to the network the interdependency risk will be reduced. Government may then choose to sell the infrastructure to the private sector for a profit.
Long-term liability	Legal and regulatory frameworks must place limits on private investors' exposure to any long-term storage liabilities. This can be achieved by transferring these liabilities to the state after a specified period of post-closure. Jurisdictions can specify a number of minimum years for which operators must continue to monitor the site post-closure. Another way in which this can be managed is through a risk capping mechanism whereby the private sector operator would be responsible for risks incurred below a cap, whilst Government would take responsibility for all additional risks above that cap. The value of the cap could be a function of the balance of public and private equity in the storage operation, with higher private equity translating to a higher cap.

TABLE 1 POLICY RESPONSES TO DEAL WITH HARD TO REDUCE RISKS[i]

ZOË KNIGHT

HSBC,
Centre of Sustainable Finance

Existing and planned infrastructure stock in power and industry are set to consume 95 per cent of the carbon emissions allowance for limiting global warming to 1.5°C if no deep decarbonisation solution is provided[15]. The IEA estimate that CCUS deployment for Paris goals will require investment of around USD9.7 trillion[16].

Heavy industry in particular is taking steps to decarbonise energy use and capture emissions associated with operations. CCS – coupled with supportive regulatory policies – is the versatile technology that enables the tangible reductions needed in these sectors. Not only does CCS align financial flow to net-zero goals but international climate agencies, like the IPCC, agree that a low-carbon transition will likely not be achieved without it. Now is the time to be innovative and drive sustainable solutions within industry, finance and beyond, and CCS will be the vehicle to help in that effort.

> Now is the time to be innovative and drive sustainable solutions within industry, finance and beyond, and CCS will be the vehicle to help in that effort.

3.2.2 INTERNATIONAL CLIMATE POLICY

While the impact of the COVID-19 pandemic has caused delays in international climate policy processes, the sizable economic recovery packages in response to it have brought climate change to the forefront of investment decisions. There is a unique opportunity to scale up funding for climate action, including for CCS.

The next Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change (UNFCCC) has been postponed for a year, to November 2021. COP26 will focus on:

1. Raising global climate ambition
2. Finalising the Paris Agreement rulebook – the implementation rules for its Article 6 on cooperation between countries
3. Getting the implementation of the Paris Agreement up and running.

The updated Nationally Determined Contributions (NDCs), officially due by end of 2020, are expected to highlight countries' commitments to tackling climate change and show the progress in global ambition. Beyond the ambition ratcheting mechanism and the negotiations on Article 6, global process is now switching into implementation mode to deliver on the goals of the Paris Agreement.

CCS technologies play a dual role under the Agreement by reducing emissions and delivering carbon removals[12]. Article 6 allows countries to work jointly in achieving their targets, including by using international carbon markets to trade emissions reductions and carbon removals, both of which can be delivered with CCS projects. The finalisation of the implementation rules on Article 6 at COP26 would provide more clarity and options for this collaboration. Given the UK's strong leadership in planned CCS projects, its COP26 Presidency is well positioned to highlight their role.

So far, 11 countries (Bahrain, China, Egypt, Iran, Iraq, Malawi, Mongolia, Norway, Saudi Arabia, South Africa and United Arab Emirates) have included CCS in their NDCs. As the timeframe of the current NDCs is relatively short (2030 or even 2025), more countries are likely to soon highlight CCS during the next round of updates, targeting 2035 and beyond.

Increased recognition of the role of CCS on the path to 2050 and beyond is obvious in the long-term low-greenhouse-gas emission development strategies (LEDS) under the UNFCCC. As of November 2020, CCS is included in 15 of 19 submitted strategies from the European Union and the following countries: Canada, Czechia, Finland, France, Germany, Japan, Mexico, Portugal, South Africa, Singapore, Slovakia, Ukraine, UK and the US. The LEDS also include more CCS references to solutions for negative emissions, including BECCS and DACCS. Once net-zero emissions are achieved, countries will need to start delivering net negative emissions, so carbon dioxide removal technologies will only increase in importance.

The scientific work of the IPCC on their upcoming Sixth Assessment Report (AR6) was also impacted by the COVID-19 pandemic. The Institute has actively participated in the expert review process of the Working Group III report which covers climate change mitigation. This report will include the latest information on the role of CCS technologies in global decarbonisation and be approved after COP26.

As the reality of delivering net-zero targets settles in, the interest in carbon dioxide removal technologies like BECCS and DACCS has substantially increased. The potential to reduce GHG emissions and balance residual emissions with removals is not spread evenly worldwide. Therefore, countries will need to work together to balance their emissions cooperatively, and the framework of Article 6 of the Paris Agreements can facilitate this collaboration in the decades to come.

3.2.3 LEGAL AND REGULATORY UPDATE

In the past year, only a slim number of countries have taken steps to develop CCS-specific legislation or improve their regulatory frameworks. Despite this, important developments at both international and national level will finally address a prolonged legal and regulatory obstacle to transboundary movement.

TRANSBOUNDARY MOVEMENT OF CO_2 ENABLED UNDER THE LONDON PROTOCOL

The 2006 amendment to the London Protocol, enabling the storage of CO_2 in sub-seabed geological formations, was an important step by the international community in recognising the potential role for CCS in mitigating climate change. It did not, however, remove all barriers. It became apparent to those seeking to export CO_2 for storage, or host storage projects within their territory, that this was not permitted.

In October 2009, an amendment to the Protocol was proposed to allow transboundary movement of CO_2 for storage, but it was not ratified by enough Parties. There was an impasse until October 2019.

At the October 2019 meeting of the Contracting Parties to the Protocol, the issue was raised once again, and a proposed resolution jointly submitted by the governments of the Netherlands and Norway. Under this proposal, Parties would allow 'provisional application' of the 2009 amendment, giving "consent to cross-border transport of carbon dioxide for the purpose of geological storage without entering into non-compliance with international commitments". Formal agreement was reached.

Countries who wish to export or receive CO_2 for storage now can; subject to providing a declaration of provisional application and notification of any agreements or arrangements to the International Maritime Organization. Effectively, the Parties will implement the provisions of the 2009 amendment before it enters into force.

REMOVING BARRIERS TO AUSTRALIAN PROJECTS

The Australian Commonwealth and Victorian governments developed some of the world's first examples of CCS-specific legislation. The Commonwealth and state offshore Acts, together with their accompanying regulations, amended existing petroleum regimes and introduced a CCS-specific model to regulate pipeline transportation, injection and storage activities within both Commonwealth and Victorian state waters.

A particular challenge of this regulatory model, however, was identified by the Victorian CarbonNet project, where a proposed storage formation straddled the boundary between a State's coastal waters and Commonwealth waters. Resolution of this issue had proven critical for the project in progressing its permitting activities and specifically, for its preferred 'Pelican' storage site.

The issue has now been addressed by the passing of Federal legislation that will allow for the grant and administration of single greenhouse gas titles, where they are partly located in both Commonwealth and State/Territory coastal waters. The new provisions will now see the title area become Commonwealth waters for all purposes of the Commonwealth's offshore regime, in instances where a new title is granted. While applicable throughout Australia, these amendments will have particular resonance for the CarbonNet project and undoubtedly assist the project's progress.

RELEASE OF GUIDANCE AROUND US TAX INCENTIVES

Proposed Treasury regulations, released by the Internal Revenue Service (IRS) in May this year, offer information and much-needed clarification as to how taxpayers, capturing and storing CO_2 under the 45Q tax provisions, can claim credit. They follow the IRS's February release of Notice 2020-12 and Revenue Procedure 2020-12, which were covered in the Institute's '*The US Section 45Q Tax Credit for Carbon Oxide Sequestration: An Update*'[13]. The Institute's update provided important detail on the definition of 'commencement of construction' of a capture facility, and guidance around the treatment of partnership structures and associated revenue procedures.

The guidance and proposed regulations contain a wealth of technical detail, but the key points are:

- Who may claim the 45Q credit
- Requirements in relation to secure geological storage
- Utilisation of carbon oxide
- Recapture of credits.

The proposed regulations address many of the remaining issues identified by investors and project developers. Although intended for use after publication, taxpayers may choose to apply and rely upon them "for taxable years beginning on or after February 9, 2018"[14] if they are followed in their entirety and applied consistently.

A more detailed overview is provided in the Section 4.1 of this report.

URGENCY

Project experience has emphasised the importance of both certainty and pragmatism within legal and regulatory regimes governing CCS operations. As outlined earlier, delays in addressing discrete legal issues, even in jurisdictions where CCS-specific frameworks have been developed, have resulted in considerable uncertainty and significant barriers to CCS deployment.

With national climate commitments, particularly net-zero policy ambitions calling for CCS, these legal and regulatory regimes must be completed in many countries and, in other cases, developed. Where governments have signalled commitment, work must progress, meeting the needs of both regulators and project proponents.

Developing CCS-specific legislation has proven to be time-consuming and resource-intensive for many governments, requiring substantial programmes of review and consultation. For nations with policy ambitions for the technology, but who are yet to consider their legal and regulatory response, there is growing urgency to begin.

3.3 GLOBAL STORAGE OVERVIEW

Geological storage of CO2 uses the same forces and processes that have trapped oil, gas (including naturally occurring CO2) and other hydrocarbons in the Earth's subsurface for millions of years.

GEOLOGICAL STORAGE RESOURCES FOR CO_2 IN SALINE FORMATIONS IS HUNDREDS OF TIMES LARGER THAN THE RESOURCES OF OIL OR GAS FIELDS SHOWN IN THIS FIGURE.

FIGURE 10 CO_2 STORAGE RESOURCES (MILLIONS OF TONNES) OF MAJOR OIL AND GAS FIELDS[k]

The last, and most critical step in CCS is the permanent storage of carbon dioxide in porous rock formations. Geological storage of CO_2 uses the same forces and processes that have trapped oil, gas (including naturally occurring CO_2) and other hydrocarbons in the Earth's subsurface for millions of years. Any formation big and deep enough (deeper than 800m) with adequate porosity and permeability, is a potential storage site as long as other impermeable rock formations prevent CO_2 escaping.

OIL AND GAS FIELDS

Many CCS projects store their CO_2 in oil and gas fields, not only because they have already demonstrated their capacity to contain CO_2 (and other fluids) for millions of years, but also because a great deal is known about them, courtesy of a century of exploration by the oil and gas industry. Structures have typically been characterised by collecting seismic data, and via analysis of geophysical data and cores taken from wells. Exploration has allowed estimation of the physical structure of rock formations, located where the best potential CO_2 storage sites may be, and offered insights into how easily fluids flow through storage rock. This is known with a high degree of confidence because:

- Production rates for oil or gas are a very strong indicator of the rate at which CO_2 can be injected into the same structure
- The total amount of oil or gas produced provides a good first estimate of the amount of CO_2 that can be stored in the structure.

Global geological storage capacity for CO_2 is many times larger than what is required for CCS to play its full role in supporting the achievement of net-zero emissions under any scenario. Figure 10 summarises the storage resources of major oil and gas fields based on the latest national and international reports, considering the mass of oil or gas in place, or already produced, (freeing up storage capacity), and the difference in density between CO_2 and oil and gas.

SALINE FORMATIONS

While oil and gas fields have the capacity to meet global CO_2 storage requirements; their geographic distribution is relatively limited. There are many instances where the distance between a CO_2 source and the nearest oil or gas field is large, increasing the cost of transport. Rock formations similar to those in oil or gas fields, but containing poor quality water instead of hydrocarbons, are much more widely spread. These saline formations are common and have vast CO_2 storage resources – several thousands of billions of tonnes of CO_2 compared to the hundreds of billions in oil and gas fields. For further reading on this topic, review studies by the US Department of Energy (USA's 2015 Storage Atlas[17] and the Crown Estate in the United Kingdom (UK CO_2 Stored)[18].

Unfortunately, as saline formations have no or low economic value, there has been almost no investment in researching their storage potential. This is another example of the CO_2 externality market failure resulting in insufficient investment in an activity beneficial to society. There is an urgent need for governments to establish programmes that appraise saline formations in the same way that gas and oil field formations have been. It would be ideal to see national portfolios that list and describe all CO_2 storage resources, with enough data to support commercial CCS investment decisions.

COMMERCIALISING CO_2 STORAGE

Two leading examples of the commercialisation of CO_2 storage resources are the Northern Lights project in Norway and the CarbonNet project in Australia. Both involve identifying and appraising geological storage resources for a future user pays CO_2 transport and storage business.

A commercially relevant classification system for geological storage resources has been developed by the Society of Petroleum Engineers (SPE). The SPE Storage Resources Management System (SRMS) is based on the SPE Petroleum Resource Management System (PRMS) used widely to classify oil and gas reserves and resources. The SRMS sets out standardised definitions to describe the maturity of, and level of uncertainty or confidence in, storage resource assessments. It supports commercial CCS investment decisions in the same way that the PRMS does for oil or gas resources.

GLOBAL CO_2 STORAGE RESOURCE CATALOGUE

The Oil and Gas Climate Initiative (OGCI) is funding the world's first application of the SRMS; the Global CO_2 Storage Resource Catalogue. It is being developed by Pale Blue Dot Energy and the Global CCS Institute using publicly available data and studies. So far, Pale Blue Dot Energy has assessed 500 sites in 80 basins across 13 countries. Within the next five years, every major storage basin in the world will be evaluated. More than 12,000 billion tonnes of potential CO_2 storage resources (*Undiscovered* is the term used in the SRMS) have been identified. Of that, only 400 billion tonnes of storage resources have had enough data collection and analysis to be classified as *Discovered Resources*, reiterating the urgent need for national programmes.

Analysis to date supports the generally held view that 98 per cent of global storage resources are in saline formations. In other words, the figures shown in Figure 10, added together, may represent around just two per cent of potential global storage capacity.

STORAGE CAPACITY IS NOT A CONSTRAINT

Geological storage resources for CO_2 appear more than sufficient to meet global requirements under any net-zero emissions scenario. However, policy settings do not support a private business case for investment. Government funding of strategic storage resource appraisal programmes is essential.

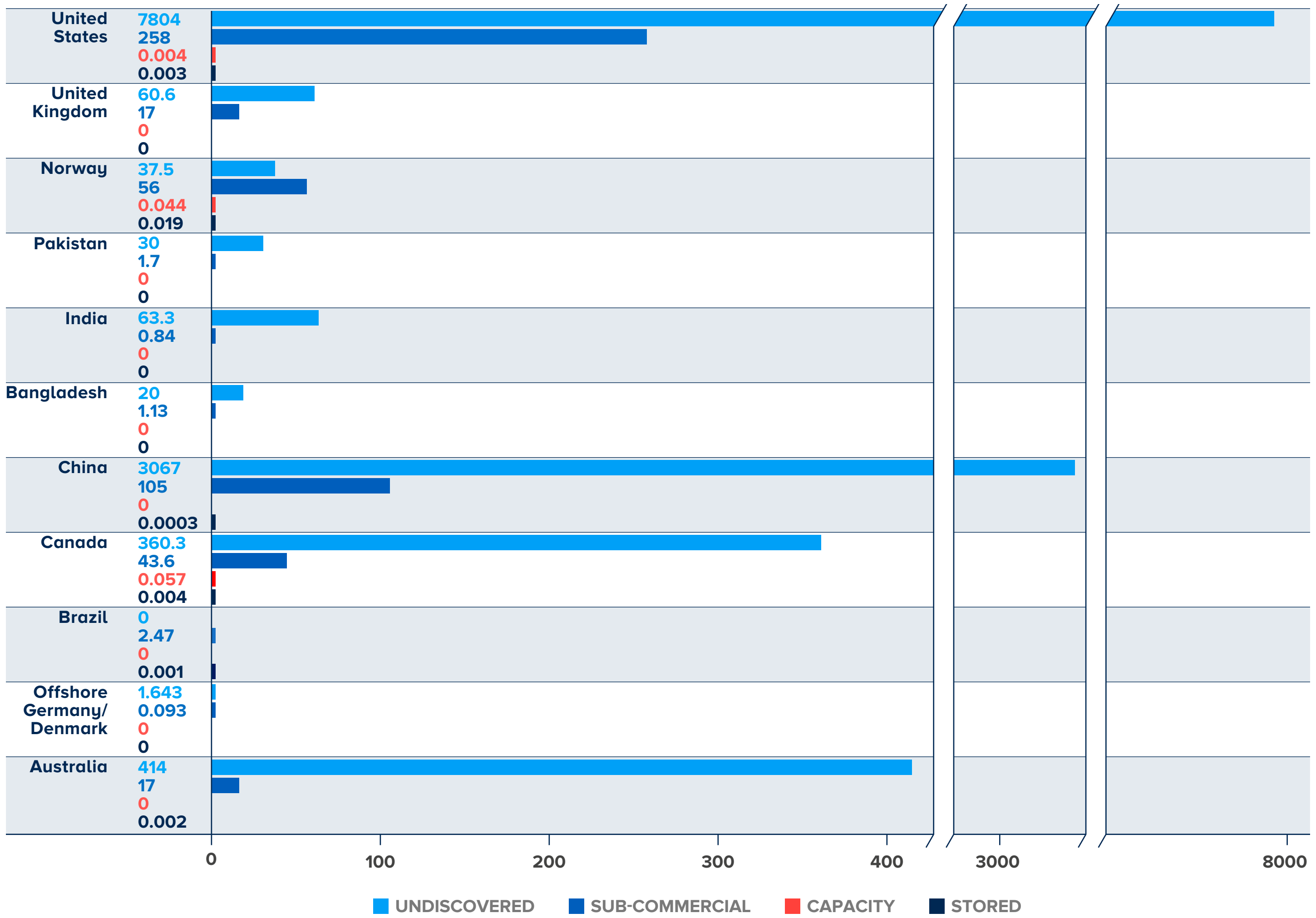


FIGURE 11 GLOBAL STORAGE RESOURCE ASSESSMENT ($GtCO_2$)[m]

PROFESSOR NIALL MCDOWELL

Imperial College

As 2020 draws to a close, so too does an induced experiment on the extent to which behavioural change can reduce anthropogenic CO_2 emissions. I'm referring, of course, to the impact of the COVID-19 pandemic. During the earlier part of 2020, a marked reduction in CO_2 emissions associated with industrial activity and air travel was observed. However, this reduction, whilst important, was far from sufficient to be a material contribution to climate change mitigation. To me, the conclusion seems clear – behavioural change alone is insufficient; technological intervention will be required to decarbonise the global economy. Beyond this, there is now a well-articulated imperative to "build back better" from the economic damage wrought by the pandemic, and that the economic recovery must also be a green recovery.

It is also vital that the green transition be – in perception and in fact – a progressive recovery. In this context, the creation of high quality jobs and the preservation of communities is of paramount importance, with a careful eye on the potential for disruptive automation. Finally, we must recognise that there is no such thing as a "one size fits all" transition. Different countries and regions have their own strengths that will need to be catered to if these aims are to be achieved. It is in this context that CCS has a uniquely important role to play in decarbonising the provision of heat, power, mobility, and industrial services, whilst creating and preserving jobs at all levels of the economy.

> **CCS has a uniquely important role to play in decarbonising the provision of heat, power, mobility, and industrial services, whilst creating and preserving jobs at all levels of the economy.**

DR FATIH BIROL

Executive Director,
International Energy Agency

> **...the IEA has identified that reaching net-zero emissions will be virtually impossible without CCUS.**

Despite the heavy toll wrought by COVID-19, I am increasingly optimistic that a clean energy future is within reach. This is in large part because more and more governments and companies are throwing their weight behind clean energy technologies, including CCUS. Almost $4 billion has been committed to CCUS in 2020 alone, including in the Longship project – Norway's largest ever climate investment.

This is good news as the IEA has identified that reaching net-zero emissions will be virtually impossible without CCUS. Its contribution extends right across the global energy system, with four strategic roles: (i) Tackling emissions from the very large and relatively young global fleet of energy assets; (ii) Reducing the most challenging emissions from heavy industry; (iii) Scaling-up low-carbon hydrogen; and (iv) Removing carbon from the atmosphere to balance emissions that cannot be avoided or eliminated.

Enhanced global collaboration will be needed to build on recent momentum and turn CCUS into a clean energy success story. The IEA is committed to playing its part in these efforts.

4.0

REGIONAL OVERVIEWS

4.1 AMERICAS

CCS FACILITIES IN THE AMERICAS

In 2020 the Global CCS Institute added 12 new commercial projects in the Americas to our database of CCS facilities.

There are now **38 commercial facilities in operation**, or various stages of development in the region. This represents around one half of the total projects around the globe.

38 COMMERCIAL FACILITIES

The **versatility of CCS** is evident in the US in 2020, projects were announced on: **cement manufacturing, coal-fired power plants, gas-fired power plants, waste-to-energy plants, ethanol facilities, chemical production.**

CO_2 CAPTURE

Operational commercial CCS Facilities in the region have a capture capacity of over **30 million tonnes per annum**.

CO_2 30 Mtpa

KEY US POLICY

New projects were, in large part, incentivised by the **45Q tax credit** and the **California Low Carbon Fuel Standard (LCFS)**

45Q CO_2 STORAGE TAX CREDITS

2020 is the year that CCS was mainstreamed into energy and climate policy discussions, with support from both **Democrats and Republicans.**

US Department of Energy is another reason for the growing list of projects in development, committing or awarding more than **$270 million in co-funding agreements in 2020.**

$270M CO-FUNDING AGREEMENTS

OPERATIONAL MILESTONES

Several significant CCS operational milestones were achieved across the Americas in 2020:

Alberta Carbon Trunk Line (ACTL) in Canada **came online.**

5M TONNES CAPTURED & STORED

Shell Quest facility surpassed **5 million tonnes** of CO_2 captured and stored over 5 years of operation.

4M TONNES CAPTURED & STORED

Boundary Dam 3 CCS facility in Saskatchewan surpassed over **4 million tonnes** of CO_2 captured and stored.

14M TONNES CAPTURED & STORED

Offshore Brazil, Petrobras Santos Basin CCS facility surpassed **14 million tonnes** of CO_2 captured and stored.

In 2020, CCS momentum continued to build across the Americas. There is sustained and growing commitment to CCS and to climate change action more broadly – from both government and business – even in the face of the economic impacts of the pandemic and the severe drop in oil prices. This commitment is reflected in the growing number of CCS projects in development, as well as announcements about deep CO_2 emissions reduction goals – including net-zero emissions – by various companies.

CCS FACILITIES

The start-up of the Alberta Carbon Trunk Line (ACTL) in Canada was a big milestone, among many. A model example of a public-private partnership, the project offers a visionary view of the future of low-carbon industrial development (see case study).

The versatility of CCS was on display throughout the year, as projects were announced in cement manufacturing, coal and gas-fired power plants, waste-to-energy plants, ethanol facilities and, chemical production. During 2020, 12 new large-scale facilities in development were added to the Institute's project database from the United States alone, largely incentivised by the 45Q tax credit and the California low carbon fuel standard (LCFS). There are now 38 commercial facilities in development, construction or operation in the region – over half of the global total (see Table 2 below for a summary of those in development).

Concerns over oil price fluctuations, and the need to mitigate this risk, have caused more projects to include stacked storage or dual storage options – utilising both dedicated geological storage in saline formations and enhanced oil recovery (EOR). The 45Q tax credit and LCFS have enabled this trend, by placing a monetary value on CO_2 emissions reductions.

Support from the US Department of Energy (US DOE)[19] is another reason for the growing list of projects. In FY 2020, Congress appropriated $217.8 million for Carbon Capture, Storage and Utilisation. Using this and other prior fiscal year funds, US DOE committed or awarded more than $270 million USD in co-funding agreements: for front end engineering and design (FEED) studies, for technologies to capture CO_2 from industrial and natural gas sources, DAC, CO_2 utilisation and geological storage.

CASE STUDY: ALBERTA CARBON TRUNK LINE (ACTL) COMES ONLINE

Envisioned more than a decade ago as the backbone infrastructure of a low-carbon economy in Alberta, the ACTL became fully operational in June 2020. The system captures industrial CO_2 emissions from the North West Redwater Sturgeon refinery and the Nutrien Redwater fertiliser facility. The CO_2 is compressed and sent into a pipeline which runs 240 kilometres to oil and gas reservoirs in southern Alberta, where it is used for EOR then permanently stored.

The pipeline can transport up to 14.6 Mt of CO_2 per year, well beyond the 1.6 Mt per year currently captured. There is capacity to tie in many more CO_2 emissions sources.

The project's total construction cost was approximately CAN $900 million – it received CAN $495 million from the province of Alberta and CAN $63 million from the Canadian government. In addition to the grant funding, financial incentives that make the project commercially viable include emissions credits to reduce tax liability, and EOR revenues.

Sturgeon Refinery Aerial. Image courtesy of Alberta Carbon Trunk Line.

FACILITY	SOURCE INDUSTRY	STORAGE	FINANCIAL DRIVERS
Wabash	Fertiliser Production	Geological	45Q, LCFS
Lake Charles Methanol	Methanol Production	EOR, Geological	EOR, 45Q
Dry Fork	Power Generation-Coal	EOR, Geological	EOR, 45Q
Tundra	Power Generation-Coal	EOR, Geological	EOR, 45Q
San Juan Generating	Power Generation-Coal	EOR, Geological	EOR, 45Q
Gerald Gentleman	Power Generation-Coal	*In evaluation*	45Q
Cal Capture	Power Generation-Natural Gas	EOR	EOR, 45Q, LCFS
Velocys Bayou Fuels	Power Generation-Biomass	Geological	45Q, LCFS
Clean Energy Systems	Power Generation-Biomass	*In evaluation*	45Q, LCFS
Illinois Clean Fuels	Power Generation-Waste-to-Energy	Geological	45Q, LCFS
ZEROS	Power Generation-Waste-to-Energy	EOR	45Q
CarbonSafe Illinois Storage Hub	Multiple	EOR, Geological	EOR, 45Q
Mid-Continent Storage Hub	Multiple	EOR, Geological	EOR, 45Q
ECO2S Storage Hub	Multiple	Geological	45Q

TABLE 2 US CCS FACILITIES AND STORAGE HUBS IN DEVELOPMENT[i]

Several significant operational milestones were achieved in 2020:

- Shell Quest facility, which captures CO_2 from a hydrogen production unit at the Scotford refinery in Alberta, Canada, surpassed five Mt of CO_2 stored in its five years
- Boundary Dam 3 facility in Saskatchewan, Canada has now captured and stored more than 3.6 Mt of CO_2
- Offshore Brazil, the Petrobras Santos Basin CCS facility, quietly surpassed 14 million tonnes of CO_2 stored since inception.

There were also some setbacks for CCS facilities in the region:

- In late 2018, a fire occurred at the Lost Cabin Gas Plant in Wyoming, USA, resulting in temporary shutdown of the plant's CCS facility. Operation is expected to be restored by the end of 2020, and the CCS unit will again capture and store CO_2 at the rate of approximately 0.7 Mt tonnes per year.
- Petra Nova, the CCS facility attached to Unit 8 of the W.A. Parish power plant near Houston, Texas, began operating in 2017 with high praise for coming in on time and under budget. The facility returned to the spotlight in 2020, but for less positive reasons. A decision was made to 'pause' operations in early 2020 because of the worldwide economic shutdown caused by the global pandemic, and a simultaneous price war which drove oil prices to historical depths. Petra Nova's operator, NRG, has indicated CO_2 capture will resume when the economics improve.

DAC and carbon utilisation continue to gain traction in the CCS conversation. Interest in investment and policy support increases alongside growing recognition that both approaches are important pieces of the climate change solution. The Carbon XPRIZE, sponsored by Canada-based COSIA and US-based NRG, is culminating its four-year challenge to develop breakthrough circular carbon technologies at the end of 2020, with the announcement of the winner in early 2021.

POLICY ACTIONS IN THE US

In 2020 CCS was mainstreamed into energy and climate policy discussions, with support from both Democrats and Republicans. Support came from:

- The bipartisan Senate Climate Caucus
- The inclusion of CCS as a key technology in the Select Report on Climate Change drafted by Democrats in the House of Representatives[20]
- Bipartisan support for numerous bills to enhance the 45Q legislation (see below).

CCS is also being embraced by numerous states. Influential states like California are pledging to work faster to decarbonise power and CCS will be an essential component in a stable and reliable electricity grid. Several states have committed to achieving net-zero emissions – most recently Louisiana, the fifth largest CO_2 emitter in the US and home to a large industrial base. Net-zero emissions plans will require CCS at scale.

45Q

As noted above, the long-awaited finalisation of the 45Q tax credit regulations occurred in August. While the legislation establishing credits (ultimately worth $50 USD per tonne of CO_2 stored in saline formations, and $35 USD per tonne of CO_2 stored via EOR) was passed in February 2018, the Internal Revenue Service (IRS) took much longer than expected to work through the details. The final guidance provides the clarity and assurance that many CCS developers and investors need to move beyond preliminary stage.

While generally pleased with the outcomes of the IRS decisions, CCS proponents are seeking changes. Most immediately, an extension to the construction deadline to account for the delay in the final regulations is sought. The option of direct pay instead of a tax credit, given the reduction in the size of tax equity markets resulting from the impacts of COVID-19 on the economy and prospective developers and financiers is also a priority.

Premier of Alberta Mr Jason Kenney at the Shell Quest CCS Facility to recognise the achievement of five million tonnes of emissions safely captured and stored, July 2020. Image courtesy of Chris Schwarz, Government of Alberta.

OTHER US POLICY DEVELOPMENTS

ECONOMIC RECOVERY

There is a proposal to include funding for CCS in the various economic recovery packages that were passed, or are being considered, by Congress. To date, no direct funding has been approved.

CALIFORNIA LOW CARBON FUEL STANDARD (LCFS)

The LCFS continues to provide a significant incentive for CCS deployment. Through the first eight months of the year, a carbon credit in the LCFS traded at around $200 USD per tonne. While eligibility requirements are stringent, many new project announcements have indicated that their economics include LCFS credits[21].

STATE PRIMACY

Wyoming joined North Dakota in receiving US Environmental Protection Agency EPA approval to take primary responsibility ('primacy') for regulating the injection of CO_2 for dedicated geological storage. Receiving primacy reflects that the state has a robust system for ensuring compliance. It allows for a more streamlined regulatory approval process. Louisiana, which has a robust CO_2 injection regime and a mechanism to assume long-term liability for CO_2 storage, has also applied for primacy.

MONITORING, REPORTING AND VERIFICATION (MRV)

In April, the IRS Inspector General reported that nearly $900 million USD in tax credits previously claimed under the original 45Q regulations did not meet applicable MRV requirements. This raised concern from both supporters and sceptics of CCS and prompted calls for the new 45Q regulations to keep the more stringent standards. These were adopted.

POLICY ACTIONS IN CANADA

FEDERAL

Canada's primary climate change policy is the Pan-Canadian Framework on Clean Growth and Climate Change. Its main goal is a 30 per cent reduction in national CO_2 emissions from 2005 levels by 2030. Under the Framework are several more specific policies which provide the mechanisms for achieving its goals. The two policies with most impact on CCS deployment are:

1. The Clean Fuel Standard states a goal of reducing annual carbon emissions by 30 Mt by 2030. It sets increasingly stringent lifecycle carbon intensity requirements for solid, liquid and gaseous fuels and provides a market mechanism of tradable credits for driving CO_2 reduction efficiencies. Companies can meet their obligations in three ways: reducing emissions from fossil fuels across the lifecycle (like EOR); selling low-carbon-intensity fuels; or switching to cleaner energy sources[22].
2. The Greenhouse Gas Pollution Pricing Act (GGPPA) mandates taxing carbon emissions from the combustion of transportation and heating fuels, starting at $20 CAD per tonne in 2019 and rising $10 per year until it hits $50 CAD in 2022. The law also includes an output-based pricing system for large carbon emitters, who must pay for emissions above the national average for their industry. Individual provinces may decide whether to implement a carbon pollution price or a cap-and-trade system, as long as it meets federal minimum requirements.

PROVINCIAL

Most Canadian CCS activity is occurring in two provinces: Saskatchewan and Alberta. Both provinces have new CCS regulations equivalent to the GGPPA that came into effect in 2020:

- Saskatchewan is the only Canadian province that has not signed on to the Pan-Canadian Framework on Clean Growth and Climate Change. The provincial and federal government entered into an equivalency agreement on coal-fired electricity generation, from 1 January 2020 – at least 40 per cent of Saskatchewan's electricity generation must come from non-emitting energy sources by 2030, essentially phasing out all non-CCS coal-fired generation.
- Alberta adopted the Technology Innovation and Emissions Reduction Implementation Act (TIER), which became effective on 1 January 2020. It establishes CO_2 emissions benchmarks for large emitters and sets a price of $30 CAD per tonne emitted over established benchmarks. Facilities exceeding their emissions reduction requirement may trade Emissions Performance Credits to other regulated facilities. CO_2 emissions reductions resulting from CCS (including EOR) are eligible under TIER.
- In September, the Government of Alberta launched the $80 million (CAD) Industrial Energy Efficiency and Carbon Capture, Utilization and Storage Grant Program as part of its economic recovery plan, providing up to 75 per cent of project expenses up to $20 million.

NEWTON B. JONES

President,
International Brotherhood of Boilermakers

The International Brotherhood of Boilermakers has long advocated for carbon capture, use and storage as the best solution that can truly reduce carbon dioxide emissions and preserve jobs, economies and social stability.

CCUS makes it possible to continue moving our scientific and communal advancements, as well as our livelihoods forward. Science proves out that moving to 100 per cent renewables will result in 100 per cent failure to realise actual climate change mitigation, let alone reverse the current course. In fact, (ironically) renewables themselves rely on fossil fuels to be built and maintained, and they count on baseload power generated from fossil fuel, nuclear and other dependable sources to provide reliable energy.

Further, that "renewables-only" misguided smoke-and-mirrors approach will radically disrupt the production of vital fossil fuel-dependent goods—life-saving medical materials and pharmaceuticals among them—not to mention the direct and indirect jobs associated with fossil fuels and the economic injection they provide and are relied upon in communities around the world.

As fast as governments have been to infuse incentives and investments in renewables, it is imperative that we advocate to yet more aggressively remove financial barriers and set in motion measures to accelerate CCUS retrofit and new-build projects, which will, in turn, drive continued innovation and cost efficiencies.

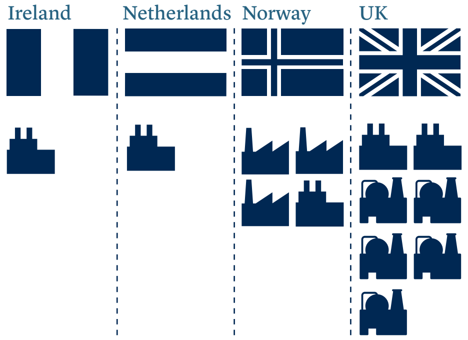
CCUS is the answer, plain and simple. Not only is it a true environmentally-impactful solution, but to meet the scale-up necessary to reach the Paris Agreement climate targets, CCUS industrial and power plant retrofits and new projects support high-wage jobs—arguably the most desirable green jobs associated with heavy industry. And that ensures our planet's survival as well as our collective societal survival.

CCUS is the answer, plain and simple.

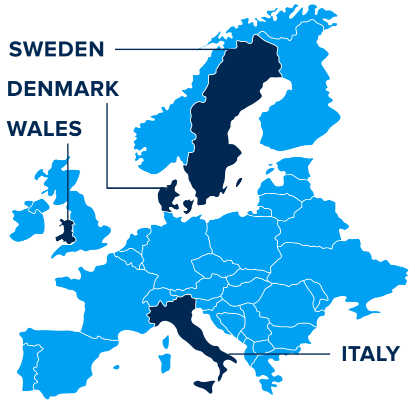
4.2 EUROPE

CCS FACILITIES IN EUROPE

13 commercial facilities in operation or various stages of development across Europe (1 in Ireland, 1 in The Netherlands, 4 in Norway, 7 in the United Kingdom).



In 2020 a number of new European projects have emerged, several in countries not typically associated with CCS such as **Italy, Denmark, Sweden** and **Wales.**



More than **11 commercial projects are targeting operation before 2030.**

POLICY DEVELOPMENTS

The unprecedented **European Green Deal and Climate law** converting the political commitment to climate neutrality into a legal obligation, has led to the development of additional EU policy supportive of CCS.

2020 saw the launch of the first call for projects under the **EU's €10 billion Innovation fund;** expected to be a major source of funding for both the planning, and the construction and operation of CCS across the EU.

Following one of the most significant global policy developments for CCS, **transboundary shipment of CO_2 will now be allowed.**

A solution enabling application of the **2009 amendment to the London Protocol** was agreed late 2019. (Consequently) Northern Lights can accept international shipments of CO_2 and has become integral to the decarbonisation of industry across Europe.

Steady progress continues to be made on the UK CCUS deployment pathway action plan, **£800m funding will be provided to establish CCUS clusters in at least two UK sites during the decade.**

With this year's introduction of legislation to deliver climate neutrality by 2050 in the EU and plans to establish ambitious 2030 targets, the urgent need for CCS facilities could not be more apparent. Thankfully excellent progress is being made. Europe's politicians, industrial strategists and an increasingly informed public understand not only the necessity of CCS for climate commitments, but also its ability to protect industry and jobs.

CCS FACILITIES

In this significant year for Europe's climate ambition, the region's long sought next operational CCS facility seems within sight. With a solution to the 2009 London Protocol amendment finally found, transboundary shipment of CO_2 will be allowed. The Norwegian Government and project proponents including Equinor, Shell, Total, HeidelbergCement and Fortum Oslo Varme have now committed to move ahead with the Langskip Project (also referred to as Longship). Northern Lights, the project's transport and storage facility, will be integral to the decarbonisation of regional industry.

The Porthos project in Rotterdam is scheduled to take a final investment decision in 2021. Operations are targeted for 2023. Like the Langskip Project, Porthos aspires to enable wider CO_2 capture. Through the CO_2 TransPorts Project of Common Interest, infrastructure development to connect other nearby ports is being examined. These include Ghent, Terneuzen, Vlissingen and Antwerp, via the already well established Antwerp@C project. More than 10 other European projects target operation before 2030. Significant, and in some cases international, industrial clusters are maturing. Ports are beginning to play a major role in the deployment of CCS and the long-sought prize of CCS in gas power is progressing through the Net Zero Teesside project (see case study, p. 43).

Reflecting the growing importance emitters place on decarbonisation, founding partners Equinor, Drax and National Grid Ventures have been joined in their efforts to develop the UK's Zero Carbon Humber cluster by Associated British Ports, Centrica Storage, Phillips 66, PX Group, SSE Thermal, Saltend Cogeneration Company, VPI-Immingham LLP and Uniper. Leveraging the region's anticipated CCS infrastructure, Equinor have also announced a major hydrogen production project, 'Hydrogen to Humber Saltend' at the Saltend Chemicals plant. Initially, the project will produce clean hydrogen using a 600 megawatt auto thermal reformer equipped with carbon capture – potentially the largest plant of its kind in the world.

In late October BP, Eni, Equinor, National Grid, Shell and Total announced the formation of the Northern Endurance Partnership. With BP acting as Operator, the Group will develop offshore transport and storage infrastructure in the UK North Sea to serve the Net Zero Teesside and Zero Carbon Humber industrial clusters. Storage will utilise the Endurance saline aquifer in the Southern North Sea, one of the UK's largest and most well understood CO_2 storage resources. A bid has been submitted for funding through the UK Government's Industrial Decarbonisation Challenge.

Offering a scalable CO_2 transport and storage solution, Scotland's Acorn project is positioned to grow quickly using nearby oil and gas infrastructure; thereby minimising capital costs. The project aims to deliver both the CCS and hydrogen facilities essential to meeting Scottish and UK Government climate targets. With an established CO_2 storage licence in place, the project could be handling Scotland's CO_2 emissions from 2024.

Athos, a development led by Gasunie, EBN, Port of Amsterdam and Tata Steel, aims to develop a transport and storage network in the Netherlands' North Sea Canal industrial area. Tata Steel's IJmuiden plant will be one of the main sources, separating CO_2 from blast furnace production gases. CO_2 will be transported offshore for storage in depleted North Sea oil and gas fields or dedicated geological storage, with some CO_2 made available for things like greenhouse horticulture. Following a feasibility study in early 2020, the project explored potential storage options and interest in the network among industrial emitters. Many responses were received that encouraged progress.

Other new European projects have emerged – several in countries not typically associated with CCS. During June in Italy at a press conference at the end of the Stati Generali, which served to define policies post COVID-19 lockdown, Italian PM Giuseppe Conte referenced plans to build one of the world's biggest CO_2 capture and storage centres at ENI facilities in the Port of Ravenna, Northern Italy. Emissions will be captured from operational power and industrial plants and stored in depleted offshore gas reservoirs. It would be one of the first operational CCS facilities in Europe outside the North Sea area.

Saltend Chemicals Plant. Image courtesy of Zero Carbon Humber.

Port site Kop van de Beer, Port of Rotterdam. Photo Credit: Danny Cornelissen. Image courtesy of Port of Rotterdam Authority.

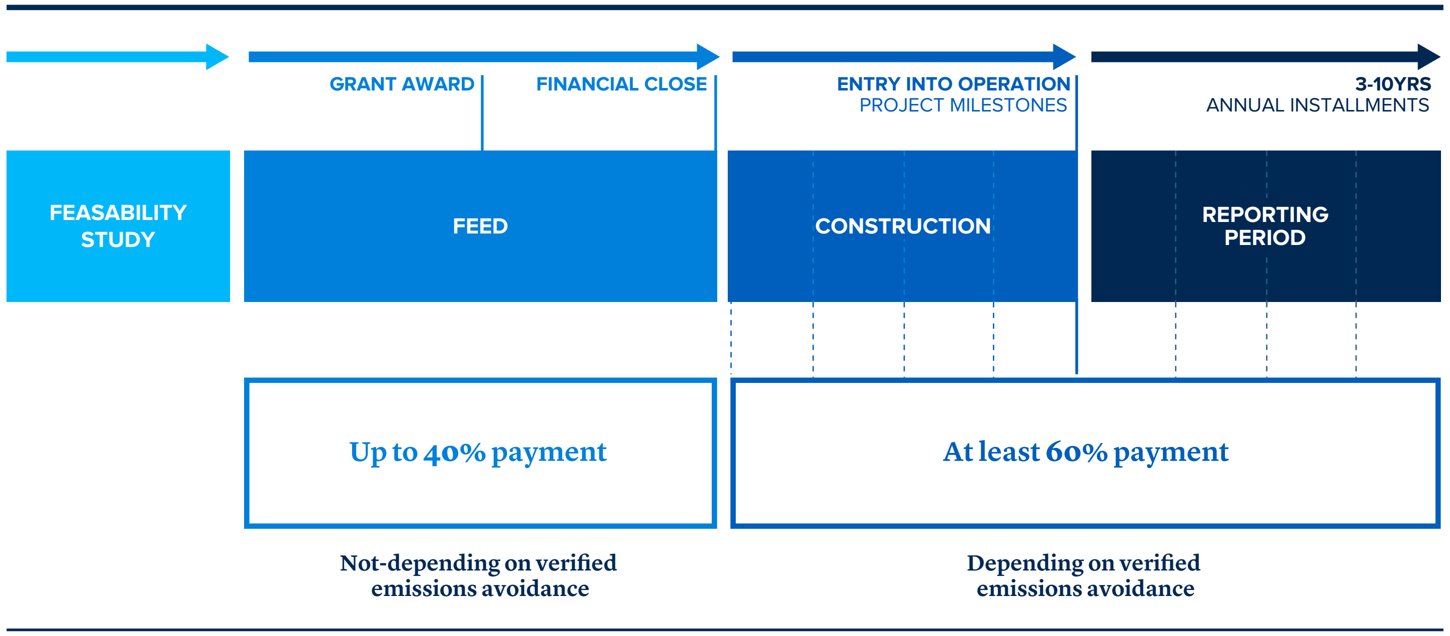


FIGURE 12 DISBURSEMENTS BASED ON MILESTONES[n]

In Denmark, CCS was presented as an important decarbonisation tool in a March report by the Council on Climate Change. A consortium of INEOS, Maersk Drilling, Wintershall Dea and GEUS was awarded funding by the Danish Energy Technology Development and Demonstration Program, supporting a project to store CO_2 in INEOS's Nini field. Project Greensand plans to re-use oil and gas infrastructure and ships for CO_2 transport. In parallel, the Amager Bakke waste to energy (WtE) plant in Copenhagen is developing plans for CO_2 capture.

The CinfraCap project in Sweden will develop proposals for open access CCS infrastructure. The project aims to develop strategies to transport CO_2 from different industrial facilities in Western Sweden, via the Port in Gothenburg, for storage via Northern Lights in Norway. Partners include Göteborg Energi, Nordion Energi, Preem, St1, Renova, and Gothenburg Port Authority.

Plans to build a net-zero cluster in Wales gained more traction when the South Wales Industrial Cluster (SWIC) was amongst six clusters awarded UK Research and Innovation funding for the first phases of the deployment and roadmap programmes. SWIC has industrial emitters from oil refining, paper production, chemicals, LNG import, steel and cement. The project is targeting additional funding through subsequent rounds of the UK Government's Industrial Decarbonisation Challenge.

POLICY ACTIONS BY THE EU

Project progress has been matched by significant policy initiatives across the region. The unprecedented European Green Deal and Climate Law, converting political commitment to climate neutrality into a legal obligation, has led to the development of more EU policy support for CCS.

July 2020 saw the launch of the first call for projects under the EU's €10 billion Innovation Fund; one of the world's largest programmes for scaling up low-carbon technologies. It is expected to be a major source of funding for CCS planning, construction and operation across the EU.

The EU's 2030 Climate Target Plan is expected to be finalised shortly. It will indicate the EU's 2030 GHG emissions reduction target and how current climate policy instruments should be updated to align with it. Corresponding proposals for revision to the EU Emissions Trading System and Effort Sharing Regulation are expected in 2021. These changes should have important implications for CCS.

Evaluation of the TEN-E Regulation is ongoing, with proposed revisions expected late 2020. This will determine whether non-pipeline transport and storage of CO_2 satisfies the criteria for Project of Common Interest status.

An EU framework for certification for carbon removals is expected in 2023. This may incentivise BECCS and large-scale DAC across the region.

At the end of May the European Commission released its proposal for a major recovery plan, *Next Generation EU*[23]. The InvestEU investment program will be upgraded and a new strategic investment facility built in. The proposal includes clean hydrogen and CCS under green technologies.

There is a proposal to increase the size of the Just Transition Fund. Facilities covered by the emissions trading scheme will be able to receive support for substantial emissions reductions – CCS included – provided they are in regions covered by the member states' just transition plan.

ALLARD CASTELEIN

CEO,
Port of Rotterdam

PORTHOS PROJECT IN ROTTERDAM IS ON TRACK

Our goals for the Porthos project are FID by late 2021 and the operational launch by early 2024. Porthos will be processing 2.5 Mt of CO_2 annually for fifteen years. The permit procedures have now begun, contracts are being signed with the clients and technical preparations are being made. Financial support from the Dutch and European authorities will ensure the finalisation of the business cases, for the Porthos project as well as for Air Liquide, Air Products, ExxonMobil and Shell, the four companies that are going to capture the CO_2. Porthos will then transport the CO_2 to empty gas fields under the North Sea for storage.

In this first phase of the project, Porthos is focusing on filling a gas field that can store 37.5 Mt of CO_2. In the following phase(s) we aim to connect more suppliers of CO_2, both inside and outside Rotterdam, and other storage fields. The announcement of stricter reduction targets in Europe will make CCS an even more important tool for combating climate change in the future. Therefore, I am confident that after this first phase of Porthos, we will soon take the next steps in the project.

> The announcement of stricter reduction targets in Europe will make CCS an even more important tool for combating climate change in the future.

POLICY ACTIONS BY INDIVIDUAL EUROPEAN COUNTRIES

There have been significant national policy developments, particularly in those countries leading European deployment: Norway, the Netherlands and the UK.

Norway's Langskip project has been enabled by widespread political support. The economic significance of CCS was emphasised by its mention in the Norwegian Government's stimulus package announced in March. In this, a commitment was made to not only accelerate Langskip, but also to support the assessment of carbon capture on incineration plants in Bergen, Trondheim and Stavanger.

In the Netherlands, the opening round of the Sustainable Energy Transition subsidy scheme (SDE++) – launching in late 2020 – will make €5 billion available for a wide range of technologies that help avoid CO_2 emissions. CCS is eligible and specific provisions have been made within the rules for its use.

Steady progress continues on the UK CCS deployment pathway action plan. The CCUS Council, along with newly established CCUS expert groups, has continued to analyse and provide guidance around the steps needed for UK deployment. In the March Budget, Chancellor of the Exchequer, Rishi Sunak, announced at least £800m will be provided to establish CCS clusters on at least two UK sites this decade. The accompanying publication[iv] indicated that consumer subsidies will be used to construct the UK's first privately financed gas CCS power station.

Following its 2020 Consultation on business models to support CCS, a response was published by the Government in August 2020. This outlined proposals for transport and storage infrastructure to be operated via economic regulation. Recognising the importance of flexible thermal electricity generation, the Government may establish a power CCS mechanism with a payment for availability and a variable payment. Industrial CCS is expected to be supported through a model that will evolve over time, initially providing upfront capital support and an industrial contract for difference. Work on these business models continues.

Other countries across Europe are examining how they might follow the region's CCS pioneers. Notably, German Chancellor Angela Merkel has stated that CCS will be necessary to reach the climate neutrality target. Home to a concentration of CO_2 intensive industry and Europe's highest emitter, CCS may be required to play a significant role in Germany's decarbonisation.

With COP26 scheduled for November next year in the UK and CCS expected to be an increasingly important feature of climate strategies, 2021 is poised to be another big year for CCS development in Europe and the UK.

Top: Norcem's Brevik Cement Plant, part of the Northern Lights CCS Project. Image courtesy of Norcem.
Above: Sembcorp Energy UK Biomass Power Station, located in Wilton International on Teesside. Image courtesy of Sembcorp Energy UK.

NET ZERO TEESSIDE – A PARTNERSHIP WITH LOCAL INDUSTRY

Based in a key industrial region in the north east, accounting for almost six per cent of UK industrial emissions, Net Zero Teesside aims to be operating by 2030. A state-of-the-art combined cycle gas turbine (CCGT) power station equipped with CCS – potentially the world's first – is central. In the UK alone, CCGTs account for over 45 Mtpa – more than 12 per cent of CO_2 emissions, so this facility's importance cannot be overstated.

Carbon dioxide from the power station, and a diverse cluster of biomass power, hydrogen production and carbon intensive industry, will be transported through a common pipeline network to permanent geological storage in the North Sea.

In September 2019, Net Zero Teesside was identified as one of five strategic hubs supported through the Oil and Gas Climate Initiative's (OGCI) important, global CCUS KickStarter programme which aims to unlock large-scale investment in CCS technology. BP, ENI, Equinor, Shell and Total are developing the project, with BP leading as operator. Key benefits include:

- Capturing up to 10 Mt of carbon dioxide annually – equal to the yearly energy use of more than three million UK homes
- Delivering flexible gas fired power with CCS – benefiting UK consumers by reducing total system costs to meet a net-zero power system by 2050
- Safeguarding 35–70 per cent of energy intensive manufacturing jobs in the Tees Valley
- Supporting £750 million in indirect and induced Gross Value Added during construction and 13,500 indirect and induced jobs annually
- Providing access to sites with more than 1000Mt storage capacity.

This year Memorandums of Understanding (MOUs) were established with local industrial emitters: CF Fertilisers, BOC and Sembcorp Utilities. Dialogue continues with others. UK Research and Innovation funds are in place for the first phases of the deployment and roadmap programmes for decarbonisation. Concept design, layout and building arrangements for the planned power station are complete and an environmental impact assessment is underway.

Two public consultations to inform proposals have been with local stakeholders – most recently running from July to mid-September 2020. Subsequently a Development Consent Order application will be submitted to the Secretary of State, Business Energy and Industrial Strategy for the necessary approvals. It is hoped the project will soon contribute to the redevelopment of one of the UK's most important industrial regions.

Net Zero Teesside, world's first zero carbon industrial hub by 2030. Image courtesy of BP and OGCI.

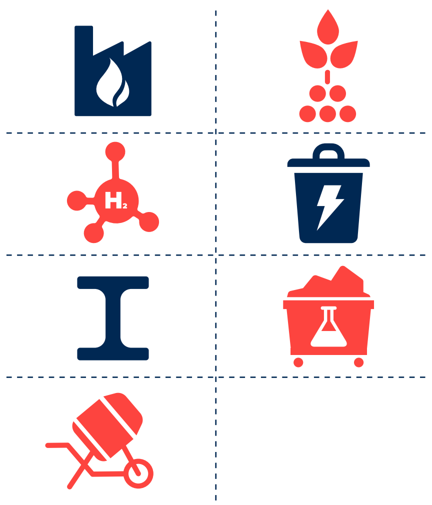
4.3 ASIA PACIFIC

CCS FACILITIES IN APAC

Asia Pacific region has **10 commercial CCS facilities** either operating or in various stages of development.

Several new commercial projects have entered engineering design or early development stages in 2020.

The region has a **great variety of CCS pilot projects**, which cover: **Natural gas processing, Fertiliser, Hydrogen production, Waste to energy, Iron/steel, Coal to chemical, Cement.**

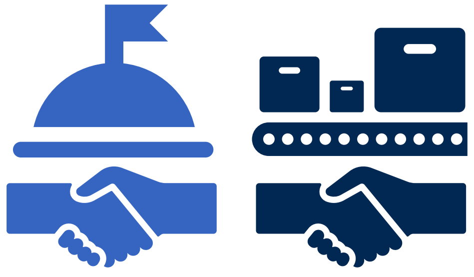


Countries that have started establishing their **CCS strategies as part of their long-term climate change commitments** include:

SINGAPORE
MALAYSIA
CHINA
AUSTRALIA

COLLABORATION

Collaboration on CCS has become a key theme for the region in 2020, this includes:
- Regional collaboration **between governments** (bilateral and multilateral)
- Supply chain collaboration **between corporations**

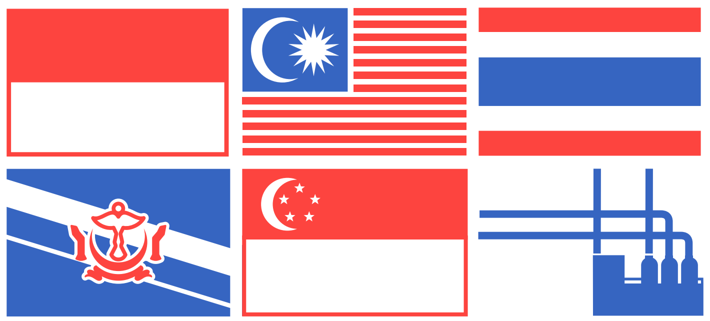


GOVERNMENT COLLABORATION

CORPORATE COLLABORATION

SOUTH EAST ASIA

Southeast Asia is emerging as a **key hub for CCUS**: Indonesia, Singapore, Malaysia, Thailand, Vietnam, Brunei.



CHINA

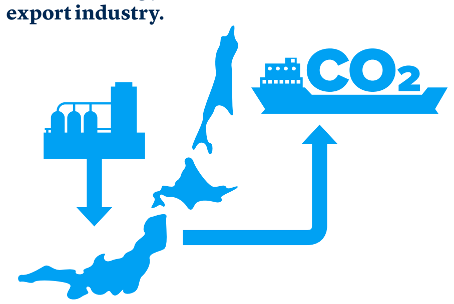
In China CCS finance, among climate finance discussions, has been a **key focus in 2020**

AUSTRALIA

Australia has seen several new projects move into different stages of the project development cycle in 2020.

JAPAN

Japan has continued to be a strong supporter and promoter of CCUS in the region and is **developing CCS technology** both for **domestic use** and as an **export industry.**



ASIA PACIFIC – THE EMERGING POWERHOUSE FOR CCS DEPLOYMENT

The past year has been exciting – and challenging – for CCS across the Asia Pacific (APAC) region. Despite government and corporate focus shifting to fighting the global pandemic, and low oil and gas prices, CCS project and policy developments in the region have demonstrated resilience.

Australia and southeast Asia are significant hydrocarbon producers, while east Asian countries are big energy consumers and host a large manufacturing industry. Although the APAC region is home to just two operating commercial CCS facilities, several new commercial projects have entered engineering design or early development. There are pilot projects in natural gas processing, fertiliser, hydrogen production, waste-to-energy, iron/steel, coal to chemical, and cement. The spread of CCS projects across sectors reflects the strength and diversity of the region's energy production and manufacturing industries.

Governments of the region have also advanced their planning and policies related to CCS' role in supporting their achievement of climate change commitments.

Developments include:

- Singapore released its low-emissions development strategy in April 2020, recognising the potential of CCS in reaching its climate change target[24].
- Malaysia is considering a regulatory framework for its high CO_2 gas field development.
- Japan embedded CCS in its January 2020 *Environmental Innovation Strategy*[25].
- China has pledged to become carbon neutral by 2060 and is currently working on its fourteenth *Five-Year plan*[26] – use of CCS is likely to be part of the recommended actions.
- The Australian Government has released several policy documents. Positive momentum to establish a policy support mechanism for CCS is building.

Regional collaboration between governments (bilateral and multilateral), and supply chain collaboration between corporations, has been a key theme across APAC in 2020. Australia and Singapore, Australia and Japan, Japan and Indonesia, Australia and China, Australia and Malaysia, all have different collaborative arrangements between governments, industry and academics. Japan, via the Joint Crediting Mechanism (JCM), is looking to support CCS projects in Indonesia (see Text Box p. 49). Collaboration in southeast Asia has helped the region better understand its storage potential. Technical assistance projects in east, south and southeast Asia, funded by development banks, have brought broader expertise to the region.

In addition, there is also growing consensus across the region that CCS regulatory frameworks are needed for long term legal certainty. Few jurisdictions currently have CCS-specific laws or laws that apply across the CCS project lifecycle. Australia is the only APAC country with a complete regulatory CCS framework. For southeast Asia, an overarching regional approach to regulation may be beneficial, offering a more uniform basis upon which national CCS-specific regulatory frameworks can be developed.

AUSTRALIA: POLICY DEVELOPMENT IN MOTION

POLICY

In February, the Australian Government published the *Report of the Expert Panel examining additional sources of low cost abatement*[27]. In its response, the government agreed to an industry consultation process on the development of a CCS methodology, under its Emissions Reduction Fund[27]. This would enable CCS project operators to compete for government funding, paid on a per-tonne CO_2 avoided basis. Formal consultation started in July seeking responses to an Emissions Reduction Fund CCS-CCUS method scoping paper.

In May, the Australian Government released the *Investment Roadmap Discussion Paper: A framework to accelerate low emissions technologies*, which discussed deployment pathways for CCS in hydrogen production and other applications[28].

The Australian Government then announced a range of measures in September designed to unlock "...new technologies across the economy to help drive down costs, create jobs, improve reliability and reduce emissions"[29]. Those measures include:

- An AUD50 million CCUS Development Fund
- AUD70.2 million to establish a hydrogen export hub
- An extra AUD 1.62 billion for the Australian Renewable Energy Agency (ARENA) and the Clean Energy Finance Corporation (CEFC) and an expansion of their focus to enable them to support a broader range of technologies including CCS. These measures require legislative amendments to be passed by the Australian Parliament.

The above announcement was closely followed by the release of the Australian Government's *Low Emissions Technology Statement* (the Statement), the first milestone in Australia's Technology Investment Roadmap[30]. The Statement prioritises "low emissions technologies with potential to deliver the strongest economic and emissions reduction outcomes for Australia", with the aim to "focus government investment on new and emerging technologies"[30]. The Statement outlined five priority technologies and economic stretch goals to make new technologies as cost-effective as existing technologies, including CCS with a stretch goal of under $20 AUD per tonne of CO_2 for CO_2 compression, transport, and storage.

Other priority technologies included in the Statement were clean hydrogen production under $2 AUD per kilogram, long duration energy storage, low-carbon materials such as low emissions steel and aluminium production and soil carbon measurement.

The Government will follow the release of the Statement with the commencement of eleven key actions, including the development of Australia's Long Term Emissions Reduction Strategy, to be delivered before COP26.

REGULATION

Australia has regulatory CCS frameworks federally and in several state jurisdictions. In May 2020, the *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Cth) (OPGGSA) was amended to enable CO_2 storage in areas straddling the three nautical mile boundary between Commonwealth and state/Territory jurisdictions. It unified and streamlined cross-boundary CO_2 injection regulation.

PROJECTS

Several new projects have progressed:

- Santos commenced FEED for its Cooper Basin Project (details in case study box below).
- Carbon Transport and Storage Company (CTSCo) is working on a 120,000 tpa full-chain CCS demonstration project, which plans to capture CO_2 from a coal-fired power station and store captured CO_2 in the Surat Basin.
- Bridgeport Energy is working toward a 1.0 Mtpa CO_2-EOR project in the Surat Basin.
- Stakeholders are looking at CCS hubs in northern and north western Australia.
- The CarbonNet Project in Victoria has completed appraisal drilling and started industry stakeholder consultation on future commercialisation options.

CASE STUDY SANTOS COOPER BASIN CCS PROJECT

Santos has commenced front end engineering design (FEED) for its CCS project in the Cooper Basin. Around 1.7 Mtpa of reservoir CO_2 produced from the Moomba natural gas processing plant will be compressed, dehydrated and transported via a 50 km pipeline to nearby depleted hydrocarbon reservoirs for storage. The project is working with South Australian regulators on permits which will test the state's CCS regulation for the first time.

Image courtesy of Santos Ltd.

SOUTHEAST ASIA: EMERGING CCS HUB

Southeast Asia is one of the fastest growing regions in the world. Its energy demand has increased more than 80 per cent from 2000, and hydrocarbon fuel (oil, coal and gas) supplies more than 70 per cent of its energy[31]. Deployment of CCS can provide the region reliable, clean and low-carbon power and decarbonise its large oil, gas and manufacturing sectors. There are encouraging low-cost early mover opportunities for large-scale CCS projects in the natural gas processing and petrochemical sectors. Due to the vast differences in economic development levels and emissions profiles among countries in this region, diverse approaches to CCS have been adopted. However, a regional hub could promote regional collaborations, achieve economies of scale and further reduce costs.

SINGAPORE

Singapore affirmed the strategic role of CCUS in its long term decarbonisation targets from technology and international collaboration perspectives in its Long-Term *Low-Emissions Development Strategy* (LEDS) in April 2020[24]. Singapore's geology is not suited to subsurface storage, and many technical and non-technical issues need to be addressed to enable trans-boundary transport and storage of CO_2. Industry stakeholders have started to investigate potential CO_2 storage sites outside Singapore and international collaboration will be key. Singapore and Australia have committed to an MOU promoting collaboration on low-emissions solutions, including CCS, in a joint statement on 23 March 2020[32].

INDONESIA

Indonesia is a large oil and gas producer and to maintain and increase production, high CO_2 gas fields will increasingly need to be accessed. This requires strategic consideration and planning for reservoir CO_2 abatement, to ensure project sustainability and commercial viability in a low-carbon future. Various internationally funded studies and pilot projects have been conducted and Indonesian oil and gas authorities are discussing CO_2-EOR and enhanced gas recovery (EGR).

In September 2020, the Japanese Government announced that it was supporting a demonstration project at the Gundih Gas field in Central Java. The project is being developed by J-Power and JANUS in cooperation with PT Pertamina and other local stakeholders. The consortium will formulate a detailed plan for a CCS demonstration project which will transport captured CO_2 from natural gas processing via a four kilometre pipeline to nearby wells for injection and EGR. This consortium is currently investigating the feasibility of applying the JCM for this project (see Japan section for further details).

A draft presidential regulation on carbon capture and sequestration was prepared by the Indonesian Centre of Excellence of CCS/CCUS with inputs from international experts and presented the Indonesian Government[33].

MALAYSIA

Applying CCS to high CO_2 gas field development has become a priority area for CCS development in Malaysia. PETRONAS, a state-owned oil and gas company and an upstream regulator[34], has been working on regulatory development around emissions limits and planning CCS projects for its high CO_2 gas fields.

PETRONAS is conducting a regional basin mapping study for CO_2 storage and working toward a large-scale offshore project near Sarawak. A final investment decision is expected in 2022.

CHINA: TIME TO GEAR UP FOR CCS DEPLOYMENT

In China's climate finance discussions, CCS financing has been a key focus. On 8 July 2020, its central bank, along with the National Development and Reform Commission and the China Securities Regulatory Commission, published *The Green Bond Endorsed Projects Catalogue: 2020 Edition*[35]. For the first time it included CCS, expanding project financing channels.

China Energy Investment Corporation started construction of its 150,000 tpa CCS demonstration project in Shaanxi Province. It will test new advanced solvents and adsorption materials for carbon capture. China has previously supported pilot projects in the power generation, natural gas processing, cement, fertiliser, and coal to chemical sectors.

Notably, CCS deployment in China is facing some difficult headwinds. Project progress has been affected by the pandemic and low oil prices. In September 2020, China pledged to become carbon neutral by 2060 and is currently working on its fourteenth Five-Year plan[24]. CCS is likely to be part of the recommended actions in this plan.

JAPAN: THE REGIONAL COLLABORATION ENGINE

Japan continues to be a driver of international collaboration in terms of clean energy, project finance, capacity development and technology transfer. In October, new Prime Minister Yoshihide Suga announced his policy for Japan to become carbon neutral by 2050 by scaling up its use of renewables and hydrogen, as well as accelerating the research and development of key technologies, including CCUS.

CLEAN HYDROGEN PRODUCTION & SUPPLY CHAINS

In addition to being a leader in the development of hydrogen utilisation technologies (eg, fuel cell electric vehicle development), Japan is driving international activities to develop clean hydrogen production using CCS, and supply chains. The Japanese Government is supporting clean hydrogen production and supply chain projects in Australia through the Hydrogen Energy Supply Chain (HESC) project, Brunei through the Advanced Hydrogen Energy Chain Association for technology Development (AHEAD) project, and in Saudi Arabia.

- The HESC project is on schedule to complete construction and commissioning of the coal gasification and gas refining facility in Latrobe Valley, Victoria Australia. In Japan, the Kobe liquid hydrogen storage and unloading terminal is completed[36].
- In April 2020, AHEAD commenced the operation of world's first international hydrogen supply chain. This involves producing hydrogen from natural gas and converting it into methylcyclohexane (MCH). The MCH is then shipped to Japan where it undergoes dehydrogenation to release the hydrogen[37]. In May 2020, regenerated hydrogen from MCH was supplied to a gas turbine in Mizue Thermal Power Plant for power generation[38].
- In September 2020, the world's first shipment of 40 tonnes of carbon free ammonia (blue ammonia which is produced using hydrogen produced from fossil fuels with carbon capture and storage) left Saudi Arabia for Japan. The ammonia will be burned in power stations to produce electricity[39].

POLICY/STRATEGY

The Japanese Government defined the role of CCS in the ground-breaking *Environmental Innovation Strategy* approved at its January Integrated Innovation Strategy Meeting[25]. The strategy includes:

- Low-cost CO_2 separation and recovery aimed toward CCS/carbon recycling
- Conversion of CO_2 to fuel and other carbon recycling technologies
- Removing CO_2 from the atmosphere.

PROFESSOR JIN HONGGUANG

Academician of China Academy of Sciences
Chair Commissioner of CCUS Professional Committee, Chinese Society of Environmental Sciences

Globally, the energy and industrial sectors must make significant changes to embrace sustainable development, reduce greenhouse gas emissions and to achieve net-zero ambitions. This monumental effort will require a diversified portfolio of technologies, among which CCUS plays a unique role. CCUS is proven to deliver massive emissions reductions. It provides a pathway for the low-carbon utilisation of fossil fuels and to achieve negative emissions, and will also make a significant contribution to clean energy production, such as hydrogen. We believe that CCUS is not only essential for CO_2 emissions reduction, but is an indispensable technology to build a resilient, versatile and complementary future energy mix.

> **We believe that CCUS is not only essential for CO_2 emissions reduction, but is an indispensable technology to build a resilient, versatile and complementary future energy mix.**

TOSHIAKI NAKAJIMA

President,
Japan CCS Co., Ltd. (JCCS)

The achievement of the Sustainable Development Goals (SDGs) as well as a zero carbon society will entail not only the advancement of energy conservation and expansion of renewables, but also the deployment of CCS to capture and store CO_2 emissions from economic activities and the social implementation of CCU and carbon recycling to utilise CO_2 as a resource.

In response to the national policy to promote CCS, JCCS conducted a CCS demonstration project in Tomakomai, Hokkaido, which achieved the target of 300,000 tonnes cumulative CO_2 injection in November 2019, confirming that CCS is a safe and secure technology.

Utilising the technology and know-how it has nurtured, JCCS will continue to engage the issues regarding the deployment of CCS, as well as contribute to the embodiment of global warming countermeasures by the Japanese government, including CCS, CCU and carbon recycling, and continue its role in communicating these efforts to the international community.

In response to the national policy to promote CCS, JCCS conducted a CCS demonstration project in Tomakomai, Hokkaido, which achieved the target of 300,000 tonnes cumulative CO_2 injection in November 2019, confirming that CCS is a safe and secure technology.

YAMASHITA RYUICHI

Director-General,
Industrial Science and Technology Policy and Environment Bureau, Ministry of Economy, Trade and Industry, Japan (METI)

According to the IEA forecast, CCS is expected to contribute 14 per cent of the cumulative CO_2 reduction by 2060. In Japan, the cabinet approved "The Long-term Strategy under the Paris Agreement" in June 2019 and set a long-term goal to reduce 80 per cent of the greenhouse gas emissions by 2050. Under this long-term goal, CCS is regarded as a technology which contributes to the significant reduction of the greenhouse gas emissions in the future. In January this year, the Japanese government developed "The Progressive Environment Innovation Strategy", aiming for the establishment of technologies that enable reduction of the accumulated atmospheric CO_2 level (Beyond Zero), as well as their social implementation to achieve the goal set in the long-term strategy under the Paris Agreement. In EU and UK as well, CO_2 reduction technologies such as CCS are regarded as crucial to achieving carbon neutrality, as there are hard-to-abate sectors such as agriculture, transport and industry.

To put CCS technologies in practical use, Japan has been making efforts to deliver a large-scale demonstration in Tomakomai, Hokkaido, carry out research and development in CO_2 separation and recovery technologies and safety control technologies, and study suitable storage sites. The demonstration project in Tomakomai, especially, has received global attention, reaching the cumulative CO_2 injection capacity of 300,000 tonnes in November 2019 and proceeding successfully in cooperation with local stakeholders. In Osaki-Kamijima, Hiroshima, a demonstration of the Integrated Coal Gasification Fuel Cell Combined Cycle has been implemented. The CO_2 separation and recovery facility was completed in 2019, and the full-scale demonstration project has started since that fiscal year. Based on the results of these efforts, Japan aims to establish the CCS technologies and bring down the cost, steadily working towards the practical application of CCS.

Looking at efforts overseas, especially in Asia, where economies continue to grow and fossil fuels are expected to remain in use, CCUS is considered essential to achieve both economic growth and decarbonization. To create a foundation from which CCUS can develop within Asia, Japan will promote Asian CCUS Network activities as opportunities to share technologies, experiences and knowledge.

Enabling practical application and commercialization of CCUS as a technology for the large-scale reduction of CO_2 emissions is vital, not only for Japan but also for the world, as a measure to combat global warming, and also important from the perspective of industrial strategy for the future. I would like to express my respect for the work of Global CCS Institute promoting the global deployment of CCS.

DOMESTIC PROJECTS

MIKAWA PROJECT

The Mikawa project is Japan's first commercial scale demonstration project and the country's first BECCS project. The project involves converting a coal fired power generator to a biomass power generation facility with CCS. An environmental impact assessment of carbon capture was done, and commissioning started in mid-2020. The project is designed to capture approximately 500 tonnes of CO_2 per day emitted by the biomass boiler.

NEW CCU RESEARCH PROJECT

An industry consortium was selected by the New Energy and Industrial Technology Development Organization (NEDO) to conduct research on recycling CO_2 from the Tomakomai City, Hokkaido refinery. The consortium will investigate the production of methanol (20 tonnes per day) from captured CO_2. Hydrogen will be sourced from refineries or from water electrolysis within the existing Tomakomai CCS facilities. The integration of CCU facilities with CCS facilities is expected to bring a benefit of sharing a carbon capture unit and enhancing the interoperability of both facilities.

INTERNATIONAL COLLABORATION: TECHNOLOGY TRANSFER AND FINANCIAL ASSISTANCE

Japan has been supporting collaborations on CCS with numerous countries in the region. Two new and important collaborative initiatives are listed below:

JOINT STUDY ON THE DEVELOPMENT OF HIGH CO_2 GAS FIELDS

Japan Oil, Gas and Metals National Corporation (JOGMEC), Petronas, and JX Nippon Oil & Gas Exploration Corporation agreed to conduct a joint study on the development of high CO_2 gas fields with CCS. The study will examine the possibility of natural gas hydrogen production and its export to Japan. JX and JOGMEC will co-operate to explore new energy value chains.

JOINT CREDITING MECHANISM STUDY IN INDONESIA

As mentioned in the Indonesian section (the Gundih Project), a Japan-Indonesia partnership was established to examine the application of JCM for a large CCS demonstration project. The project will quantify the GHG emissions reductions achieved by implementing Japan's advanced low-carbon technologies.

INDIA: ACCELERATED CATCH-UP PHASE

Capacity development and stakeholder engagement have been key themes. Technical assistance projects funded by development banks and international clean energy initiatives, have helped build an understanding of CCS and its role in decarbonisation.

India's steel and cement sectors are now proactively pursuing CCS as part of their emissions reduction ambitions. Reliance Industries Limited has announced a plan to develop CCS technology as part of its net-zero commitment[40].

In September 2020, an "Industry Charter" for near zero emissions by 2050 was agreed to by six Indian companies. The companies will explore different decarbonisation measures including carbon sequestration[41].

India's Department of Science and Technology has established a national program on CO_2 storage research and, in August, made a call for proposals to support CCS research, development, pilot and demonstration projects[42;43]. This is part of the Accelerating CCS Technologies (ACT) initiative, for which India has committed one million euros to support Indian participants. Selected projects are required to have partners from at least three ACT countries and are scheduled to start in September 2021[44].

JOINT CREDITING MECHANISM (JCM)

The JCM is a project-based bilateral offset crediting mechanism, established and implemented by the Government of Japan[45;46]. The JCM appropriately evaluates, in a quantitative manner, Japan's GHG reductions contributions or removals achieved through diffusion of low-carbon technologies, products, systems, services, and infrastructure. The JCM also implements mitigation actions in developing countries, and uses them to contribute to achieving Japan's emission reduction target.

The objective of the JCM is described in three parts[47]:

1. To facilitate diffusion of leading low-carbon technologies, products, systems, services, and infrastructure as well as implement mitigation actions, and contribute to developing countries' sustainable development.
2. To appropriately evaluate contributions from Japan to GHG emission reductions or removals in a quantitative manner and use them to achieve Japan's emission reduction target.
3. To contribute to the ultimate objective of the UNFCCC by facilitating global actions for GHG emission reductions or removals.

To date, the JCM has been established with 17 countries; Indonesia, Vietnam, Lao PDR, Myanmar, Thailand, Cambodia, the Philippines, Mongolia, Bangladesh, Saudi Arabia, Maldives, Ethiopia, Kenya, Costa Rica, Palau, Mexico, and Chile[46].

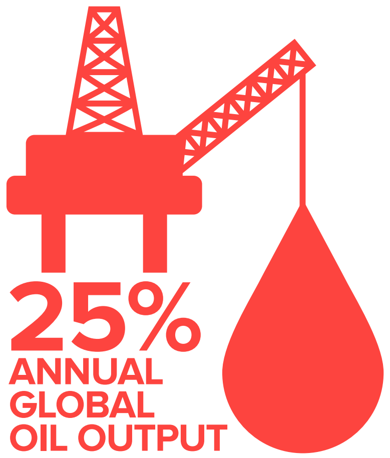
Top: Tomakomai CCS Demonstration Facility. Image courtesy of Japan CCS Co., Ltd. Above: Mikawa Power Plant. Image courtesy of Toshiba Energy Systems & Solutions Corporation (Toshiba ESS).

4.4 GULF COOPERATION COUNCIL (GCC) STATES

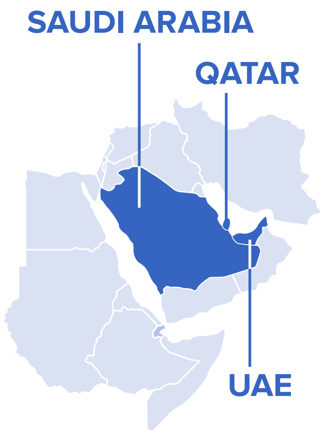
CCS OVERVIEW

Almost **three-quarters of CO_2** emissions in the region come from two states, Saudi Arabia and United Arab Emirates (UAE).

The region accounts for less than **1% of world population**, the Middle East produces around **25% of annual global oil output.**

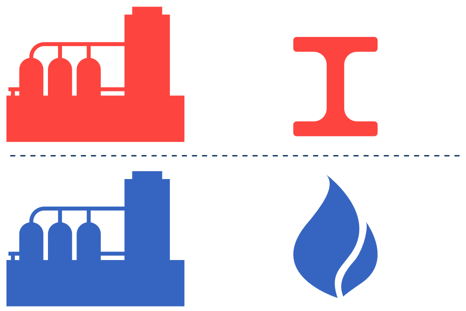


Current CCS activity is spread across three Middle East states – **the UAE, Saudi Arabia and Qatar.**



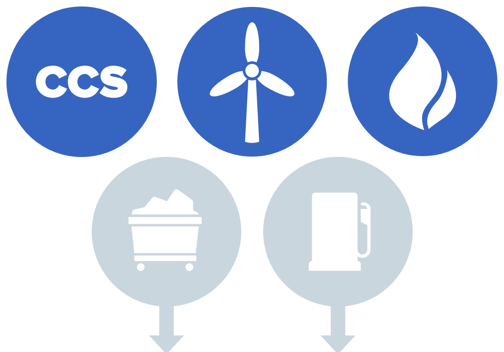
Region has **vast and accessible underground storage potential of 5-30 Gigatonnes***

3 **commercial CCS facilities** in operation:
2 in **natural gas processing** and
1 in **iron and steel production**

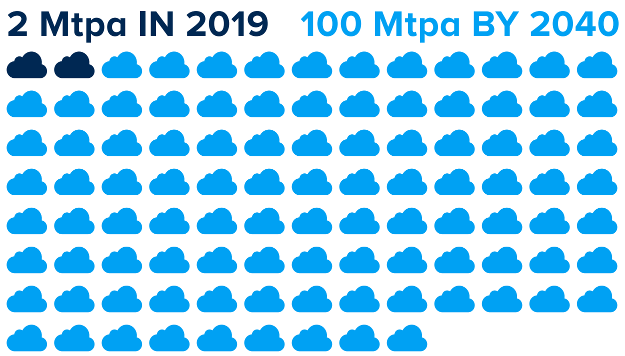


Capturing **3.7 Mtpa** of CO_2

CCS is a strong component of the key states' national low-carbon plans along with renewables, natural gas replacement of both oil and coal as well as enhanced energy efficiency.



Some projections of CCS project numbers in the region include volumes of CO_2 captured rising from around **4Mtpa in 2019** to over **100Mtpa by 2040****



*Medium confidence ** Based on commissioned evaluation from Qamar Energy, June 2019

Despite the economic challenges posed by the decline in oil and gas prices over the past 12 months, countries of the Gulf Cooperation Council (GCC) – Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman – are emerging as important actors for the short to medium term global CCS outlook. With less than one per cent of world population, these countries produce around a quarter of annual global oil output[48]. With world demand for oil and gas broadly forecast to reduce in pursuit of net-zero emissions, there is increased focus on industrial diversification and decarbonisation and all GCC countries have compelling strategic goals for achieving this.

POLICY

Commitment to action on climate change is intensifying. CCS is a strong component of the GCC countries' national low-carbon plans, along with renewables, natural gas replacement of both oil and coal, and enhanced energy efficiency[49;50;51]. CCS has a strong and central role in the Circular Carbon Economy concept that was developed in the region (see text box below).The need for significantly more CO_2 to replace natural gas in EOR-assisted oil production is another complementary driver of CCS projects[52].

Almost three-quarters of Middle East CO_2 emissions come from just two states: Saudi Arabia and United Arab Emirates (UAE)[48]. They are both members of Mission Innovation and active in the Clean Energy Ministerial CCS initiative. Both states have issued ambitious national strategies to diversify and decarbonise their economies[50;53] and submitted NDCs to the UNFCCC that explicitly mention the role of CCS[54;55]. The Kingdom of Saudi Arabia's national oil company aims to further reduce CO_2 emissions from operations to embed and improve its claims of producing oil with the world's lowest carbon footprint[56;v].

PROJECTS

Current CCS activity is spread across three states – the UAE, Saudi Arabia and Qatar:

- Around 0.8 Mtpa of CO_2 is captured from the Emirates steel plant in Abu Dhabi as Phase I of the ADNOC Al Reyadah project
- Plans for Phase II are underway, aiming to capture an additional 2.3 Mtpa from 2025, from the Shah gas processing plant, again for EOR use
- ADNOC's goal to reduce its operational CO_2 intensity 25 per cent by 2030 includes plans to grow with Phase III of Al Reyadah to capture another 2 Mtpa from the Habshan and Bab gas processing facility
- Saudi Aramco's Uthmaniyah oil production (part of the Ghawar field) uses 0.8 Mtpa CO_2 captured from the Hawiyah Natural Gas Liquids (NGL) plant[56]
- Saudi Basic Industries Corporation's (SABIC's) CCS facility at its ethylene plants in Jubail captures about 0.5 Mtpa for use in methanol and urea production
- Qatar Fuel Additive Company captures 0.2 Mtpa at its methanol refinery
- Qatar Gas announced plans at the end of 2019 to add CCS to its Ras Laffan gas liquefaction plant[57] – the initial capture rate of 2.1 Mtpa is projected to grow to 5 Mtpa by 2025

Top: Qatargas Ras Laffan LNG plant. Image courtesy of Qatargas.
Above: Hawiyah Gas Plant, Saudi Arabia. Image courtesy of Aramco.

An often-overlooked characteristic of Middle East GHG emissions is that emissions from power generation are more than double those from industry – including oil and gas activities[58]. As decarbonisation plans involve replacing coal and oil with natural gas, wind and solar, CCS could have a stronger role in power generation in this region than would be typical for the rest of the world.

Although, relative to the region's emissions and stated ambitions, actual CCS development activity remains limited, there is evidence of considerable ongoing study activity amongst energy and industrial companies. Some estimates of CCS project numbers include volumes of CO_2 captured rising from around 2 Mtpa in 2019 to over 100 Mtpa by 2040[vi]. That kind of growth would have a big impact on global CCS deployment rates and costs.

The next few years could feasibly see an unprecedented take-off of CCS in the Middle East, especially in UAE and Saudi Arabia, perhaps to the point that the region could evolve to be a critical 'global hot spot' for CCS. As regional interest in low-carbon hydrogen grows; with its vast underground storage potential[59], abundant natural gas resources and excess production capacity, the Middle East could use its developing CCS expertise and location to develop a clean hydrogen export industry. The region's rich CCS-related potential merits close attention.

ADAM SIEMINSKI

President,
King Abdullah Petroleum Studies & Research Center (KAPSARC)
Senior Advisor,
CSIS Energy Security and Climate Change Program

Even with the welcome deployment of renewables and energy efficiency, we must also make a significant effort to build the infrastructure to capture and store carbon because hydrocarbon fuels are very likely to play a significant role in the future global energy mix. The circular carbon economy (CCE) offers a pragmatic framework for meeting climate challenges by focusing on outcomes that embrace all opportunities, including CCS and direct air capture (DAC), to manage carbon emissions.

The GCC region has abundant carbon storage capacity and can play a strategic role in the necessary global scale-up of CCS. Combined with its oil and natural gas resources, the region is ideally situated to develop industrial carbon storage clusters and to produce blue hydrogen. The region's unparalleled solar resources in conjunction with ample carbon storage potential also offer the opportunity for DAC as the technology matures.

> The GCC region has abundant carbon storage capacity and can play a strategic role in the necessary global scale-up of CCS.

LEILA BENALI

Chief Economist,
Arab Petroleum Investments Corporation (APICORP)

> ...there has emerged a clear agreement in policy and energy circles that CCUS is a critical technology to reduce emissions and achieve climate change goals.

Over recent years, we have witnessed an increasing level of awareness of climate change - and even more recently of the need to reach net-zero emissions by mid-century. What I have also observed is an increased focus on how action on climate change and emissions reduction commitments work from a finance perspective.

In recent years, there has not only been a wide-spread, increasing level of awareness of climate change, there has emerged a clear agreement in policy and energy circles that CCUS is a critical technology to reduce emissions and achieve climate change goals.

When it comes to the financing of CCUS, we must forge ahead to create the mechanisms needed to stimulate investment and create the business case for CCUS. We must continue to take lessons from the past, of the scale-up of existing technologies, and rapidly begin to apply these to CCUS to drive deployment to the levels urgently required.

THE CIRCULAR CARBON ECONOMY

The circular economy concept describes a systemic means of eliminating waste by ensuring maximum continual use of resources. Many variants have been developed for specific applications.

Saudi Arabia's King Abdullah Petroleum Studies and Research Center (KAPSARC) is developing the circular carbon economy model to help contextualise the kingdom's climate policy plans[60]. It is based on the 'four Rs':

- reduce
- re-use
- recycle
- remove.

The framework recognises and values all forms of CO_2 mitigation. The 'remove' title describes options, such as CCS, DAC and improved land management that safely remove, isolate and store CO_2.

KAPSARC's work includes a new distinction between:

- living carbon' (plants and soil)
- 'fugitive carbon' (like methane and CO_2 gases)
- 'durable carbon' (for example, locked in plastics).

Each of the four Rs has an optimum role in dealing with the three classes of carbon. Although 'remove' is the last in the hierarchy of mitigation, only to be used if other options fall short, it, and specifically CCS, is considered critical to achieving net-zero emissions alongside all other options.

The Kingdom of Saudi Arabia is strongly promoting the Circular Carbon Economy (CCE) as a framework to drive a holistic "all of the above" approach to climate mitigation. KAPSARC coordinated the production of a CCE Guide[vii] describing how different technologies and approaches can support reducing emissions to net-zero. The Guide, published in August 2020, includes chapters on Non-Bio Renewables, Nuclear, Carbon reuse, Bioenergy, Carbon capture and storage, Hydrogen, and Enabling policies. Each chapter was written by the preeminent organisation in each field including the International Energy Agency, the International Renewable Energy Agency, the Nuclear Energy Agency, the Global CCS Institute, and the Organization for Economic Cooperation and Development. This report was endorsed by G20 Energy Ministers in late September 2020 in their communique noting that the Circular Carbon Economy offers "a holistic, integrated, inclusive and pragmatic approach to managing emissions that can be applied reflecting a country's priorities and circumstances.".

Development of the CCE framework is continuing. Saudi Aramco is working with the Center for Global Energy Policy at Columbia University and the Global CCS Institute to further develop the scholarship around the CCE framework, and to quantify the abatement opportunity under each of it four Rs.

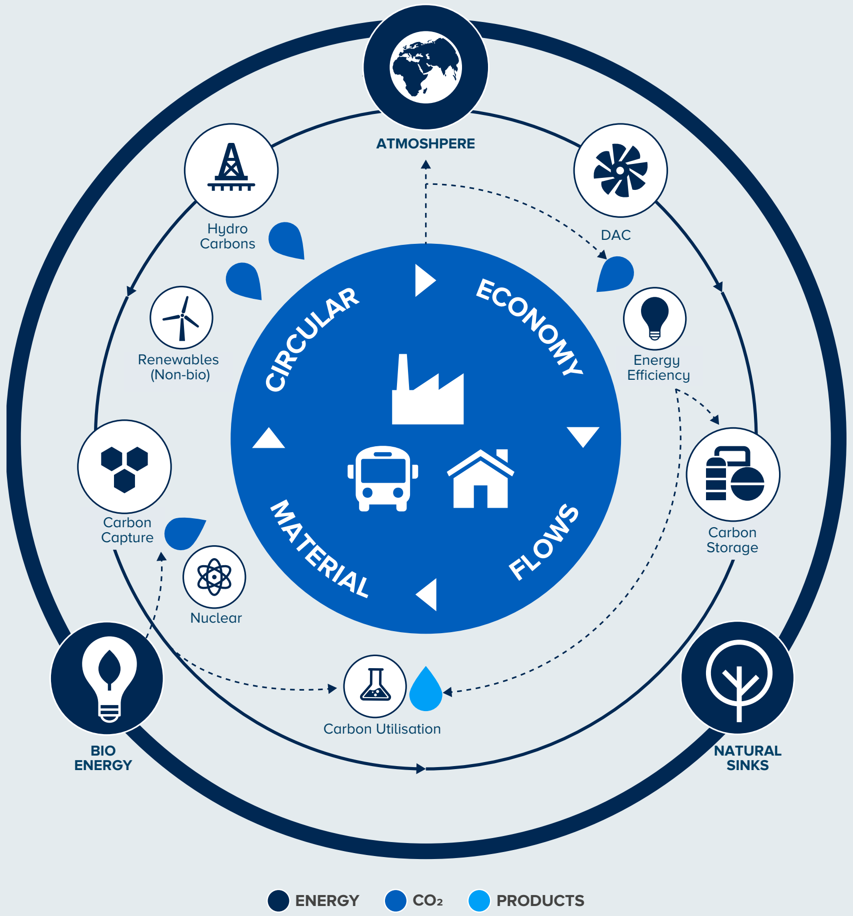


FIGURE 13 ACHIEVING CLIMATE GOALS BY CLOSING THE LOOP IN A CIRCULAR CARBON ECONOMY[O]

5.0

CCS DEVELOPMENT: TECHNOLOGY & APPLICATIONS

5.1 INDUSTRY

Industry produces about eight billion tonnes of direct CO_2 emissions annually – the cement, iron and steel, and chemical sectors are responsible for about 70 per cent of these. If indirect emissions are added, industry accounts for almost 40 per cent of global anthropogenic CO_2 emissions[15]. Demand for industrial products will grow at least through to the middle of this century, driven by an additional two billion people to feed, clothe, house, transport and entertain. Growing affluence, particularly in developing economies, will see hundreds of millions of people able to afford goods and services for the first time.

Considering current commitments in Nationally Determined Contributions (NDCs) to limit emissions and improve energy efficiency, the IEA estimates that direct industry CO_2 emissions will grow from eight to almost 10 billion tonnes per annum, by 2060. To achieve a climate outcome consistent with the Paris Agreement, these emissions should instead fall to 4.7 billion tonnes by 2060[15].

Approximately 1.9 billion tonnes of industry CO_2 emissions each year are a bi-product of chemical reactions within the production process. These ‘process emissions’ cannot be avoided using feasible production technologies. For example, 65 per cent of emissions from cement production are created when calcium carbonate (limestone) is converted to calcium oxide (lime) – the CO_2 producing chemical reaction must occur to make cement. Other examples of industrial processes with significant CO_2 emissions are natural gas processing; the production of iron, steel, ammonia/urea and biofuel; and various petrochemical processes that produce chemicals, plastics and fibres.

Multiple approaches will be necessary to cut emissions, including fuel switching, improved energy efficiency, and the deployment of current best available and future innovative technologies. The only feasible option for mitigation in many cases, is to remove CO_2 after production, using CCS.

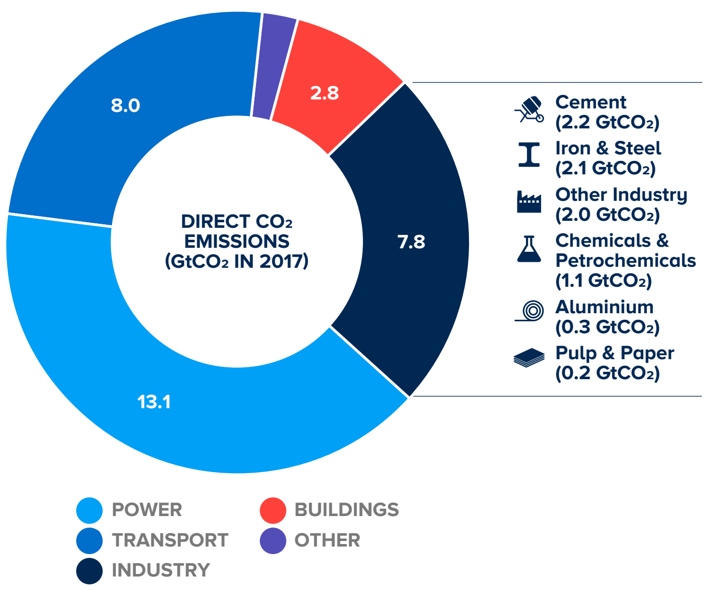


FIGURE 14 GLOBAL DIRECT CO_2 EMISSIONS BY SECTOR[viii]

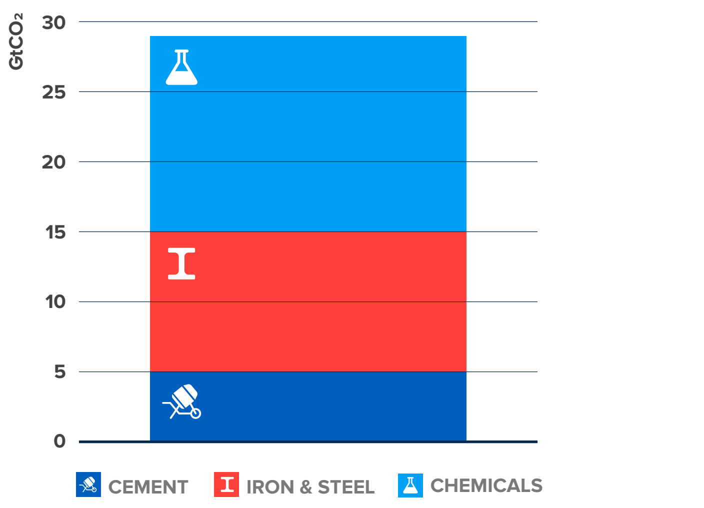


FIGURE 15 CCS CONTRIBUTION TO EMISSIONS REDUCTIONS IN THE CEMENT, IRON AND STEEL AND CHEMICALS SECTORS BETWEEN 2017 AND 2060[viii]

The IEA estimates that CCS must provide 29 billion tonnes of abatement between 2017 and 2060 in the cement, iron and steel and chemical sectors to achieve a climate outcome consistent with the Paris agreement. CCS is especially applicable in the chemicals industry, delivering 14 billion tonnes of abatement to 2060, due to several chemical production processes that produce almost pure streams of CO_2 with a very low capture cost.

CEMENT

Conventional cement making involves exposing carbonate materials, usually limestone ($CaCO_3$), to intense heat in a rotating kiln. High temperatures drive ‘calcination’, creating calcium carbonate (CaO) and CO_2. Extra CO_2 is produced also, through the combustion of fuels – usually coal or natural gas – to provide the heat needed to drive the reaction. Calcium carbonate is a key component of Portland cement, essential for the world’s construction industries.

Even if heat is provided by a biogenic or other low emissions fuel source, around 50 per cent of calcination emissions from cement making typically remain[61]. They are fundamental to the reaction that produces calcium oxide. The cement industry produces approximately eight per cent of global CO_2 emissions[62] with calcination representing around four per cent. Although alternatives to cement exist, they are only slowly being deployed. Addressing cement industry emissions is therefore essential for a net-zero world.

Flue gases from cement kilns are good candidates for CCS. Their typical CO_2 concentrations are around 14–33 per cent[61], higher than from conventional coal-fired combustion. Their higher CO_2 purity makes capture less energy intensive. Conversely, considerable processing is required to remove contaminants like cement dust.

NORCEM CCS PROJECT

In June, HeidelbergCement’s Norwegian subsidiary Norcem entered an agreement with Aker Solutions to capture CO_2 from the Brevik cement plant in Norway[64]. A proprietary solvent-based carbon capture plant will be installed to capture flue gas from the cement kiln.

Heidelberg has also been developing an oxyfuel cement kiln. Using pure oxygen instead of air in its kilns, eliminates nitrogen in the flue gas – increasing CO_2 concentration to 70 per cent or higher[64]. Higher CO_2 concentrations make any downstream CO_2 capture much more energy efficient and significantly reduce flue gas volume, cutting capital costs significantly.

PROJECT LEILAC – (LOW EMISSIONS INTENSITY LIME AND CEMENT)

In early 2020, Australian company Calix signed agreements to trial its proprietary calcination reactor technology in the LEILAC project. This will mean a fourfold scale up of its pilot plant under phase one. It represents a big step forward in cement technology and points the way to lower sector emissions.

In conventional rotary kilns for cement and lime manufacturing, combustion air is used to burn fuels at very high temperatures. The nitrogen left over from this process mixes with the CO_2 produced through calcination. Nitrogen lowers the purity of CO_2, increasing the energy and cost involved in carbon capture.

Calix’s technology physically separates the CO_2 produced through calcination from the heat source. Raw meal flows inside an inner reaction tube and is heated from outside by a separate fired heater or electrical heating source. Carbon dioxide produced from the calcination process is at all times separate from any air or nitrogen from the combustion used to provide heat. As a result, process CO_2 from the Calix calciner is dry, capture-ready and almost entirely pure. Figure 16 shows how the reactor works.

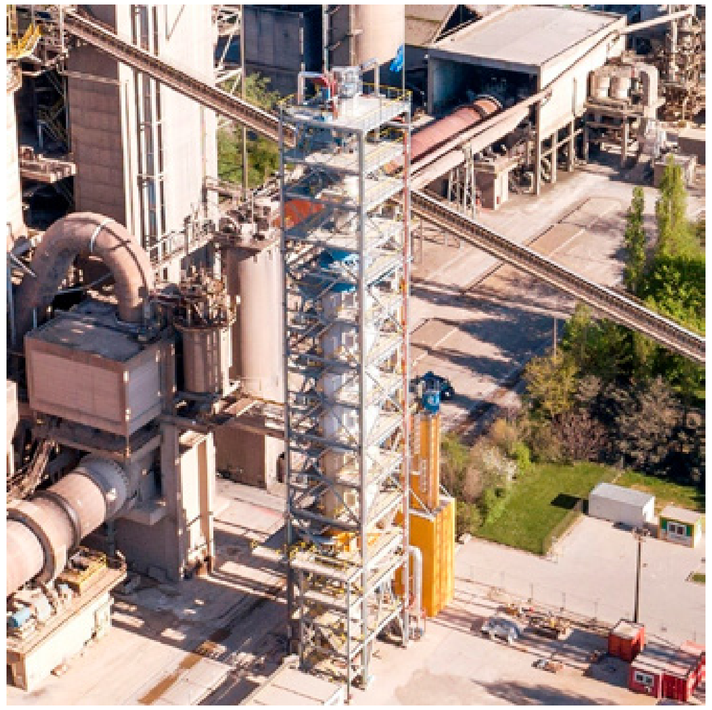
The Calix reactor can potentially be heated using renewable electricity or fired with biofuels to provide low emissions heat, dropping overall plant emissions to near-zero. Another advantage is that a Calix calciner can be incorporated into a regular cement plant, leaving the remainder as-is. This makes it a good candidate for retrofitting the world’s cement plants.

IRON AND STEEL

The iron and steel industry produces approximately seven per cent of global CO_2 emissions[65]. Considerable efforts are being made to reduce these through measures like steel recycling, energy efficiency programs, and early steps toward substituting fossil fuel for hydrogen. A large portion of GHG emissions can be addressed using CCS.

The Emirates steel plant in Abu Dhabi has been operating a solvent-based CCS plant since 2016. Carbon dioxide is produced by the coal or natural gas that acts as a reducing agent in the DRI (direct reduced iron) unit – transforming iron ore to elemental iron for use in steelmaking. The Emirates steel plant captures approximately 0.8 Mt tonnes of CO_2 per year and transports it by pipeline for EOR.

Other projects are looking at changing the underlying process of steelmaking to facilitate CO_2 abatement. The Hisarna process, operated by Tata Steel, is a new technology that not only increases energy efficiency and reduces the emissions intensity of steelmaking, but also increases CO_2 concentrations. This makes it much easier to capture.



Calix advanced calcination reactor at their LEILAC pilot plant in Belgium. Image courtesy of Calix.

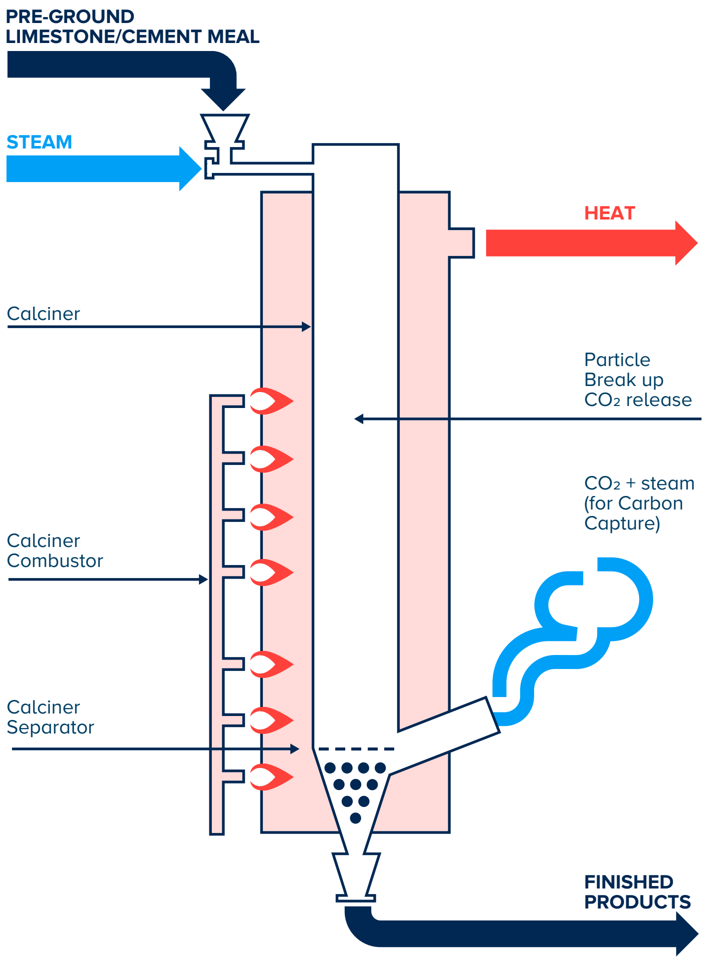


FIGURE 16 CALIX ADVANCED CALCINATION REACTOR – DETAILED VIEW
Source: Calix (supplied)

DR YITING SUN

Standing Member,
Climate Investment and Finance Association
of Chinese Society for Environmental Sciences

China aims to have CO_2 emissions peak before 2030 and to achieve carbon neutrality before 2060. Carbon capture and storage (CCS) has been accepted as a scalable solution to facilitate achieving these ambitious climate targets. For industrial sectors reliant on fossil fuel energy, are able to well manage their climate risks and, when CCS technologies become commercially available, have the financial strength and regulatory support to deploy CCS. Steady, and growing, investment will allow CCS technologies to advance. Companies, such as leading oil and steel producers, have already acted on the opportunities and are investing in CCS development. A bright future for CCS in China is expected, with favorable policy, advanced technology and enhanced investment creating enabling conditions for its deployment.

> A bright future for CCS in China is expected, with favorable policy, advanced technology and enhanced investment creating enabling conditions for its deployment.

5.2 HYDROGEN

In recent years hydrogen has become one of the most talked about trends in global energy. It is an energy carrier – much like electricity – that must be manufactured from primary or secondary energy sources.

Hydrogen is sometimes considered the chemical twin of electricity. Zero GHGs are produced when hydrogen is used – just like with electricity. And, like electricity, the production of hydrogen can cause emissions upstream from the end-user. Supply chains for this 21st century commodity must therefore be carefully developed.

Although use is limited now, there is significant potential for cost-effective, low-emissions hydrogen. It is expected to play a critical role in replacing hydrocarbon-based fuels in heavy and long-range transport vehicles (trucks, buses) where batteries are impractical. It will also help resolve the big challenge of decarbonising high-temperature industrial heat, mostly produced now by natural gas and coal. It could be a storage medium for power generation, with some also used as an additive to conventional natural gas supplies.

HYDROGEN PRODUCTION AND MARKETS

Production of pure hydrogen reached 70 Mt and total hydrogen (including syngas) 120 Mt in 2020[66]. Most was used in oil refineries and chemical production.

Ninety-eight percent of current hydrogen is produced from coal (via gasification) and by steam methane reforming (SMR) from natural gas. Both processes produce significant CO_2 emissions if abatement is not used. Both are well suited to economical CO_2 emissions abatement with CCS. A very small portion (0.3 per cent) is produced from electrolysis of water, powered by renewables.

Figure 17 shows the shares of hydrogen production today:

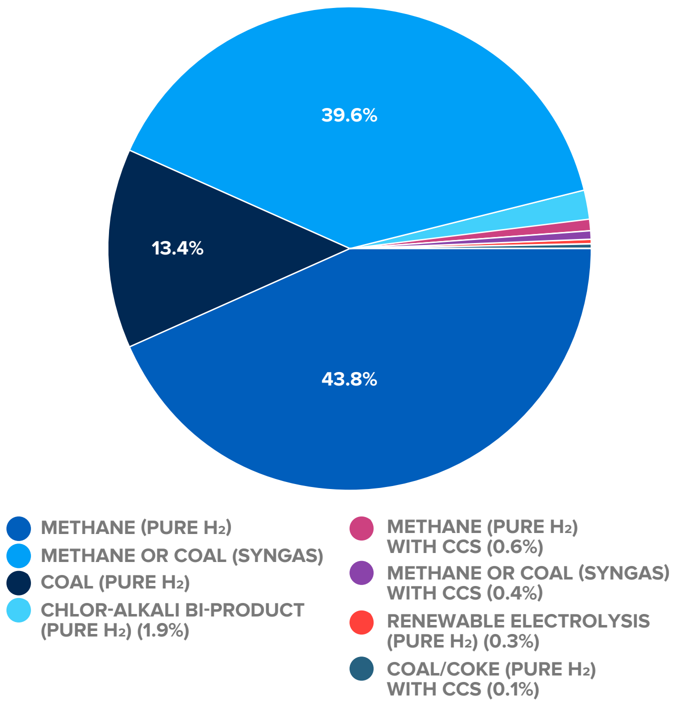


FIGURE 17 GLOBAL SHARES OF HYDROGEN PRODUCTION FROM DIFFERENT SOURCES AND PROCESSES[p]

ALL COSTS IN USD PER KG OF HYDROGEN	DEDICATED RENEWABLE ELECTRICITY SUPPLY	OTHERWISE CURTAILED RENEWABLE ELECTRICITY SUPPLY	STEAM METHANE REFORMATION WITH CCS	BLACK COAL GASIFICATION WITH CCS
CSIRO 2018	$7.70	$18.20	$1.80	$2.00
IEA 2019	$3.75	–	$2.00	$2.00
IRENA 2019	$4.10	–	$2.50	$2.00
Hydrogen Council 2020	$6.00	–	$2.10	$2.00
Simple average of costs from these four reports	$5.40	$18.20	$2.10	$2.00

TABLE 3 SUMMARY OF COSTS OF HYDROGEN PRODUCTION FROM VARIOUS LOW-EMISSIONS PATHWAYS[q]

LOW EMISSIONS HYDROGEN PRODUCTION

Three main routes are available for hydrogen production:

- Reforming of natural gas
- Gasification of coal or coke
- Electrolysis of water (aka water splitting).

Approximate hydrogen cost estimates, from reputable sources[67,68,69,70], are summarised in Table 3. These estimates are only indicative and should be treated with caution. The basis for each cost estimate (assumed capacity factors and fuel costs) differs between reports, and in some cases, reports present a range of costs. For example, the figure quoted for the IEA in the table is an average of costs given for different parts of the world.

CCS-equipped coal gasification and SMR pathways are much lower cost than electrolysis from renewables. IRENA estimates that renewables-based hydrogen should be competitive with hydrogen produced by SMR, or coal gasification with CCS, by 2050[70]. With enormous pressure to achieve net-zero by 2050, and a large existing unabated fleet of gas and coal-based hydrogen production, the move to large-scale low emissions hydrogen will require significant deployment of retrofitting, and new CCS plants.

A key low-emissions route for hydrogen production is SMR coupled with CCS. Today there are four industrial-scale SMR hydrogen facilities with CCS worldwide, producing a total of around 800,000 tonnes of low-carbon hydrogen per year[71]. One of these SMR with CCS facilities is Air Products' Port Arthur, Texas hydrogen plant, a two-train SMR facility which captures CO_2 from its reformer units using vacuum swing adsorption[72]. This plant has a carbon capture capacity of almost one Mt per year, providing CO_2 for EOR operations.

Coal gasification with CCS is a well proven technology for mass production of hydrogen, with low emissions. Three facilities produce hydrogen from coal, coke or asphaltene (similar to coke) with CCS – combined capacity approximately 600,000 tonnes of hydrogen per year. The world's largest clean H_2 plant is Great Plains Synfuel in North Dakota, US, producing 1300 tonnes per day of hydrogen from the gasification of lignite (brown coal). This mature facility has been producing hydrogen since 1988 and capturing CO_2 for storage since 2000. Approximately three Mt per year is transported to Saskatchewan, Canada for EOR.

Air Products' Port Arthur Texas Hydrogen Plant. Image courtesy of Air Products and Chemicals, Inc.

Operations like Port Arthur and Great Plains Synfuel demonstrate that large-scale production of low emissions hydrogen using CCS, is economically and technically feasible, already.

GROWING DEMAND FOR LOW EMISSIONS HYDROGEN

For hydrogen to make a meaningful contribution to global GHG emissions reductions, very large quantities must be produced to displace a large proportion of currently unabated fossil fuel use. Annual demand for low-emissions hydrogen could grow to 530 Mt by 2050, reducing annual CO_2 emissions by up to six billion tonnes[73]. However, abatement benefits are only possible if hydrogen is produced using near zero-emissions processes. Currently, less than 0.7 per cent of hydrogen production is from renewable energy (via electrolysis) and fossil fuel plants equipped with CCS[15].

HYDROGEN PRODUCTION WITH CCS

Steam methane reforming (SMR) is a mature technology. Hydrogen is produced by a reaction of methane and steam at high temperature, followed by a water-gas shift reactor to further convert carbon monoxide and steam into more hydrogen. Figure 18 below shows a typical process flow diagram for an SMR hydrogen plant.

CO_2 can be captured from SMR plants in three locations:

- In the shifted syngas at high pressure (1)
- In low-pressure tail gas (2)
- In the flue gas from burning fuel to provide heat for the SMR unit (3).

The Port Arthur facility captures CO_2 from shifted syngas (1), taking advantage of the high concentration and pressure of the CO_2, to minimise capture costs.

Typically, around 40 per cent of CO_2 emissions from SMR come from flue gas (3). This is more expensive to capture as the CO_2 is dilute and at low pressure. It can be achieved with conventional post-combustion style technologies.

Coal gasification to produce hydrogen, occurs in gasifier reactors. These subject coal to high temperatures with limited oxygen, causing 'pyrolysis reactions' that produce carbon monoxide and hydrogen. After a shift reactor converts carbon monoxide to CO_2, followed by further treatment and hydrogen separation, CO_2 is produced at high purity.

For gasifiers operating at elevated pressures, the high pressure of the CO_2 is a distinct advantage. It reduces the costs of operating downstream compression equipment because much of the pressure has already been provided by the gasifier.

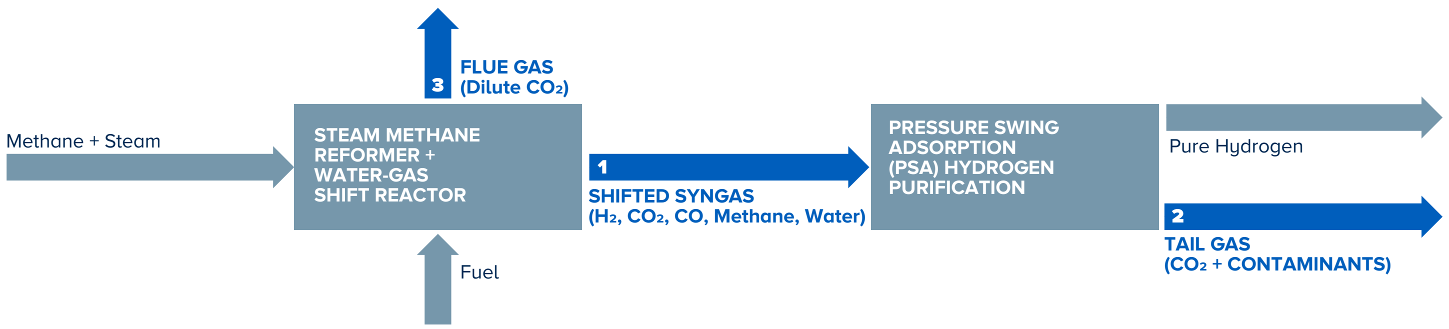


FIGURE 18 BLOCK FLOW DIAGRAM FOR SMR-BASED HYDROGEN PLANT

EMISSIONS ABATEMENT OPPORTUNITY COST OF USING RENEWABLE ELECTRICITY TO PRODUCE HYDROGEN

Most renewable energy technologies produce electricity. This electricity can be used directly to displace fossil fuel-based power generation in a power grid. If renewable electricity is used instead, in water electrolysis to produce hydrogen, there will be an abatement opportunity cost – renewable electricity producing hydrogen will not be available to displace fossil-fuel electricity emissions.

Figure 19 is an analysis showing the abatement possible through direct use of renewable power in a grid (displacing fossil fuel generation) vs the abatement possible if renewables-based electrolysis hydrogen is used to displace natural gas combustion[ix].

Using renewable energy to replace fossil-fuel based generation in a power grid, provides three to eight times as much abatement benefit as can be achieved by using renewable energy to make green hydrogen which then replaces combustion of natural gas. The most effective and powerful path is to produce hydrogen from natural gas or coal with CCS, and reserve renewables for electricity grids.

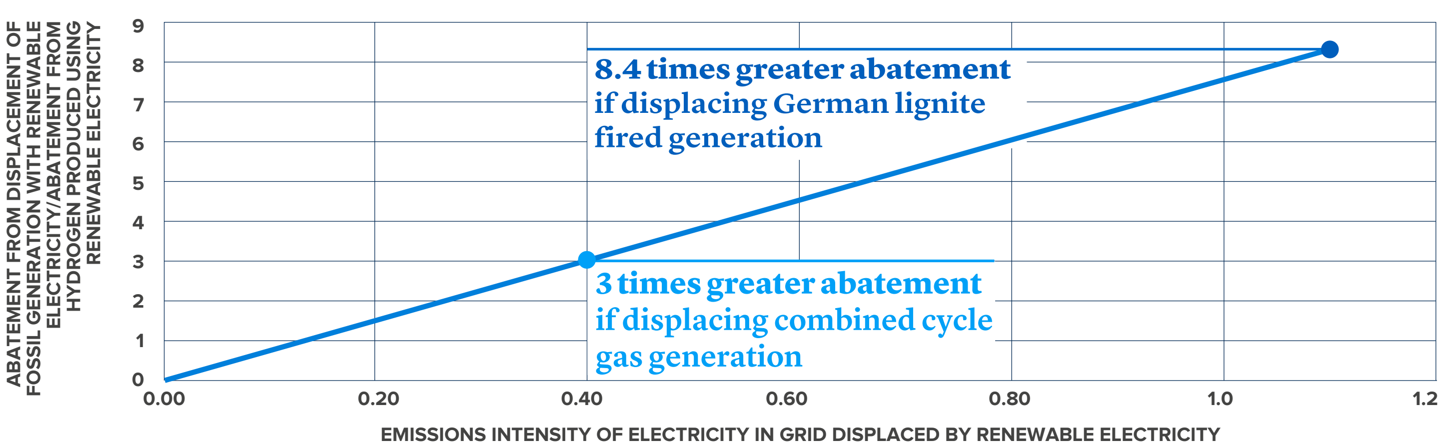


FIGURE 19 RENEWABLE ELECTRICITY USED TO DISPLACE FOSSIL GENERATION DELIVERS SIGNIFICANTLY MORE ABATEMENT THAN RENEWABLE ELECTRICITY USED TO PRODUCE HYDROGEN

Assumes hydrogen displaces combustion of natural gas

5.3 NATURAL GAS

This year saw the single largest shock to the global natural gas market in history. The COVID-19 pandemic has significantly depressed demand across the world, with a four per cent drop in demand growth for natural gas anticipated[74]. However, demand should recover and increase by around 14 per cent by 2025, compared to 2020[75]. It is expected to keep growing beyond 2025 as a result of primary energy demand growth, particularly in Asia, and due to gas replacing coal in North America and, to a lesser extent, in Europe.

The switch from coal to gas reduces CO_2 emissions at point of use by about half, but gas production and processing can have significant emissions, both from the use of energy at processing facilities and from the way gas is produced. Raw natural gas typically contains CO_2 – sometimes in significant quantities. This must be removed before the natural gas can be sold and is typically vented to the atmosphere. Around 150 Mtpa of high purity CO_2 is released from gas processing plants around the world[76].

As this CO_2 is available at high purity, it typically only requires dehydration before it can be compressed and stored. This makes it a low-cost source to capture and store – in the order of US $20–25 per tonne[77]. In locations where a plant is close to the CO_2 injection site (less than 50 km) and storage is on-shore, costs of US $15–$20 tonne for compression, transport and storage would be expected[x].

Without CCS, CO_2 emissions from gas production will continue to grow in line with increasing demand for gas. Further, there is likely to be a general trend toward producing gas from conventional reserves that contain higher concentrations of reservoir CO_2, increasing the emissions intensity of gas production. CCS is the only way to mitigate those emissions.

Australia is a good case study in the growth of emissions from gas production and processing, and the role CCS can play in mitigating them. Exports of liquified natural gas (LNG) from Australia increased from 23.9 Mt in 2014 to 77.1 Mt in 2015, causing a doubling in fugitive emissions from the Australian oil and gas sector (17.4 $MtCO_2e$ to 33.7 $MtCO_2e$), as shown in Figure 20[78].

A CCS facility at the Chevron Gorgon LNG plant in Australia was commissioned in August 2019. Its impact on emissions is clearly visible in the December 2019 quarter in Figure 20. In its quarterly update of Australia's GHG inventory, the Australian Government notes that the decrease in emissions was:

"*...driven by total gas production decreasing 5.4 per cent in the December 2019 quarter....The increasing ramp up of underground carbon dioxide injection from the Gorgon project during the December quarter also reduced fugitive venting emissions.*"[79]

With a capacity of 3.4–4 Mt of CO_2 injection per year, the Gorgon CCS facility is a significant abatement project for the Australian gas industry. It is now one of the largest operating CCS facilities anywhere in the world[80]. Facilities like Gorgon will be required across global gas production to achieve net-zero emissions.

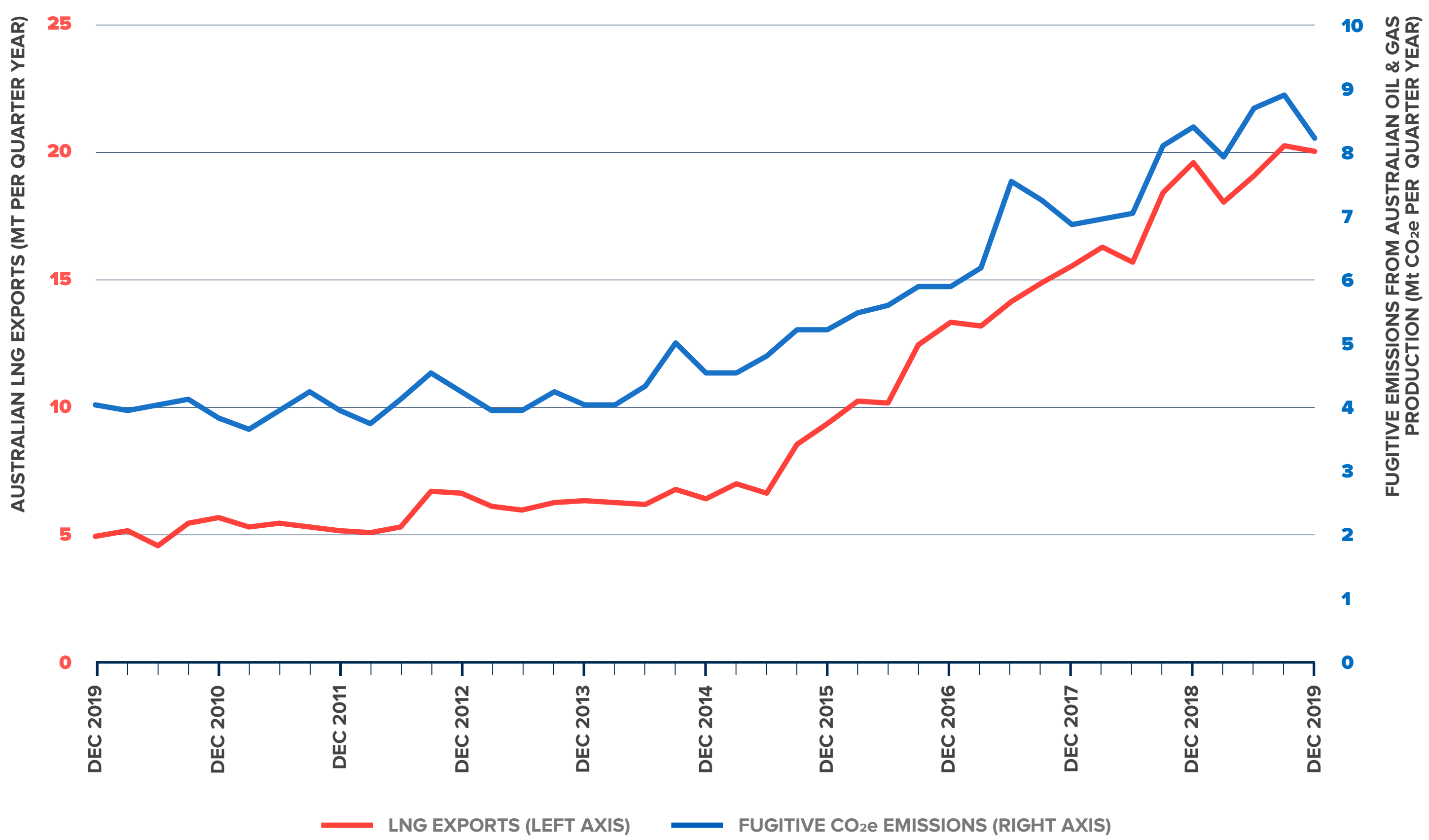


FIGURE 20 AUSTRALIAN LNG EXPORTS AND FUGITIVE EMISSIONS FROM AUSTRALIAN OIL AND GAS PRODUCTION

5.4 CCS IN THE POWER SECTOR

The rapid decarbonisation of power generation is crucial to achieving net-zero emissions. Electricity generation accounts for around a third of global CO_2 emissions. Already the largest source of CO_2 emissions globally, demand for electricity is forecast to increase significantly.

CCS equipped power plants will help ensure that the low-carbon grid of the future is resilient and reliable. Flexible power plants with CCS supply dispatchable and low-carbon electricity as well as grid-stabilising services, such as inertia, frequency control and voltage control. These cannot be provided by non-hydro renewable generation. CCS complements the increased deployment of intermittent renewables.

CCS is also essential for reducing emissions from the global fossil fuel power fleet we already have. Globally, there is approximately 2,000 GW of operating coal-fired capacity, with over 500 GW of new capacity expected by 2030. Over 200 Gt of new capacity is already under construction. While some coal and gas plants will be retired early, the average age of the natural gas fleet is 19 years in Asia and coal plants only 12 years[75]. They have decades of economic life left. Without CCS retrofit or early retirement, coal and gas-fired power stations – current and under construction – will continue emitting CO_2 at rates that will consume 95 per cent of the IEA's Sustainable Development Scenario (SDS) carbon budget by 2050. Achieving net-zero emissions will be impossible.

Retrofitting fossil fuel generation with CCS can be a cost-effective option in some cases. It means economies that are heavily dependent on coal – such as China, India, and countries in southeast Asia – can continue using it while moving toward a low-carbon economy, thereby supporting a just transition.

ALLAM-FETVEDT CYCLE PROVIDES PROMISING PATH TO LOW-EMISSIONS, LOW-COST POWER FROM COAL OR GAS WITH CCS

The Allam-Fetvedt Cycle is an innovative natural gas (or syngas from gasification of coal) fired power generation technology with inherent CO_2 capture. It involves oxy-fuel combustion and using the CO_2 this produces as the working fluid. This means in-built CO_2 capture, compression and dehydration as well as the elimination of NOx and SOx[81,82].

This technology can produce electricity with more than 97 per cent CO_2 capture at a levelised power price approximately 22 per cent higher than today's conventional natural gas combined cycle[xi]. The cost premium is expected be under 10 per cent by 2050.

At its heart, the Allam-Fetvedt Cycle uses a specialty turbine running on supercritical (high pressure and temperature) CO_2 instead of the steam used in conventional power generation plants.

The technology produces pipeline-ready CO_2 without the need for add-on carbon capture equipment. NET Power LLC is currently commercialising the Allam-Fetvedt Cycle in the natural gas industry while 8 Rivers Capital is leading an industrial consortium in North Dakota and Minnesota to apply the Allam-Fetvedt Cycle to syngas from coal/biomass/petroleum coke gasification. Nearly all components of an Allam-Fetvedt Cycle plant are commercially available, except the turbine and combustor. Toshiba developed, manufactured and supplied a hybrid turbine and combustor for use in the gas-fired pilot project in Texas.

8 Rivers Capital plans to use the Allam-Fetvedt Cycle and 8 Rivers hydrogen technology for co-production of power and H_2 using natural gas feedstock. 8 Rivers Capital is currently completing engineering studies for an integrated power, hydrogen and fertiliser plant with CCS at Pouakai in New Zealand[83].

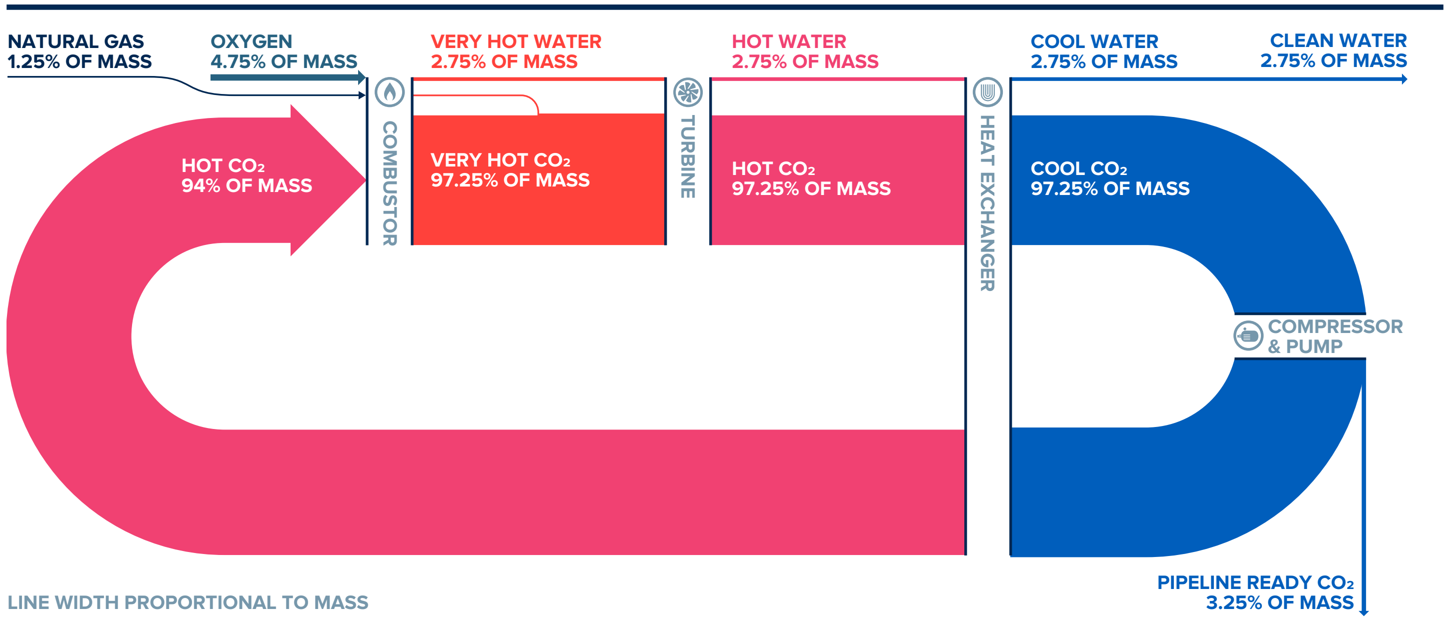


FIGURE 21 THE ALLAM-FETVEDT CYCLE PROCESS FLOW
Source: 8 Rivers Capital (supplied)

NET Power's Pilot Project in La Porte, Texas. Image courtesy of NET Power.

The first Allam-Fetvedt Cycle combustor using supercritical CO_2 as a working fluid was tested at 5 $MW_{thermal}$ scale in 2013. In March 2018, Net Power announced that it had successfully fired its 50 $MW_{thermal}$ first-of-a-kind natural gas-fired Allam-Fetvedt Cycle power plant located near Houston, Texas. The design of a commercial-scale 303 MW Allam-Fetvedt Cycle natural gas plant is underway. A pre-FEED study for an Allam-Fetvedt Cycle power production facility for potential deployment at multiple locations in the UK was announced by McDermott in June 2020[84].

5.5 NEGATIVE EMISSIONS TECHNOLOGIES

The global trend of commitments to future scenarios with 'net-zero' emissions will present some significant economic and technical challenges.

Most of humanity's industrial, energy and agricultural systems produce a net increase in atmospheric GHG. Even low-emissions technologies like nuclear, hydropower, fossil with CCS, wind and solar electricity have net-positive lifecycle GHG emissions. For net-zero to be achievable, it is essential that negative emissions technologies be deployed, as well as low and zero emission energy sources. Negative emissions mean that an activity is a net remover of CO_2 from the atmosphere. Two key negative emissions technologies include BECCS and DACS.

BIOENERGY WITH CCS (BECCS)

The principle of BECCS is that biomass is grown and used for energy purposes. As biomass is either formed, or derived, from photosynthesis, it absorbs atmospheric CO_2. The biomass is then processed into a fuel. As the fuel is combusted, the carbon it's made of, forms so-called 'biogenic' CO_2. Biogenic CO_2 is typically counted as a net-zero emission in most GHG accounting schemes.

Therefore, if some of the biogenic CO_2 is captured and stored, this is a net reduction of CO_2 from the atmosphere. Figure 22 on the following page describes an example of a BECCS process – in this case capturing CO_2 from fuel processing and fuel use.

Biogenic CO_2 can be produced through fuel processing (for example CO_2 from fermentation to produce bioethanol) and from fuel use (CO_2 from direct combustion of biofuel). In the case of ethanol fermentation, very high CO_2 concentrations can be reached.

Most of the world's BECCS facilities involve the capture of fermentation CO_2 from ethanol plants. It is high purity and typically only requires dehydration before it can be compressed for transport and storage. This makes it a very low-cost CO_2 source for capture.

The Illinois industrial CCS facility in the US is a good example of an operational BECCS plant. Carbon dioxide produced as a by-product of large-scale corn-to-ethanol processing at the Decatur ethanol plant, is compressed and stored in a nearby geological storage structure. CCS capacity at this facility is one Mt per year.

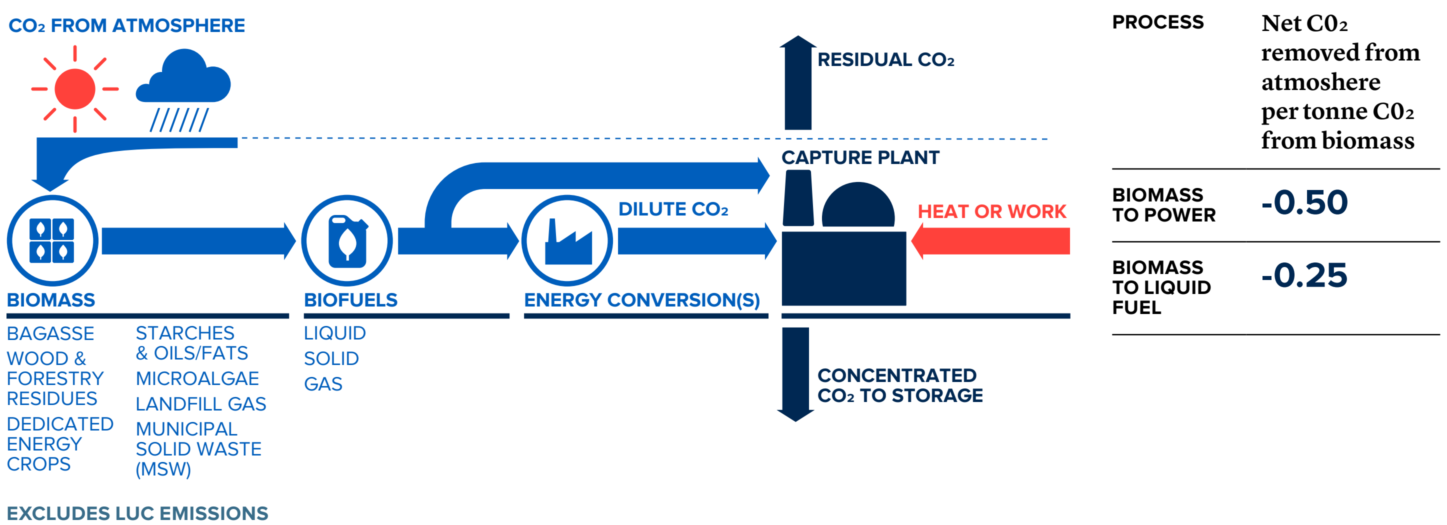


FIGURE 22 THE BECCS PROCESS

Waste-to-energy (WtE) plants are another area of growth potential for BECCS. WtE plants use sorted municipal solid waste as a fuel for thermal power generation and low-grade heat for nearby homes and businesses. A significant fraction of the incoming waste-based fuel will be of biogenic origin, including paper, cardboard, wood, food waste and garden trimmings. If a WtE plant can capture and store a higher proportion of its CO_2 than is produced from the combustion of fossil-fuel origin waste (i.e. plastics), then the plant's overall emissions become negative. This makes the plant a net reducer of atmospheric GHGs, a source of useful heat and power, and a way to reduce the burden on limited landfill space.

Thousands of WtE plants are operating worldwide. Most are a modest size, making the need for economic small-scale capture plants vital for increasing deployment of CCS (refer to Modularisation in Section 5.6 CCS Innovation).

A key CCS project is underway at the Twence WtE plant in the Netherlands. Using Aker's Just Catch modular carbon capture plant, CO_2 will be captured from flue gas (illustrated at 5.6 below). The capture plant capacity will be 100,000 tonnes per year and the plant is expected to be commissioned in 2021[85].

DIRECT AIR CAPTURE WITH CARBON STORAGE (DACCS)

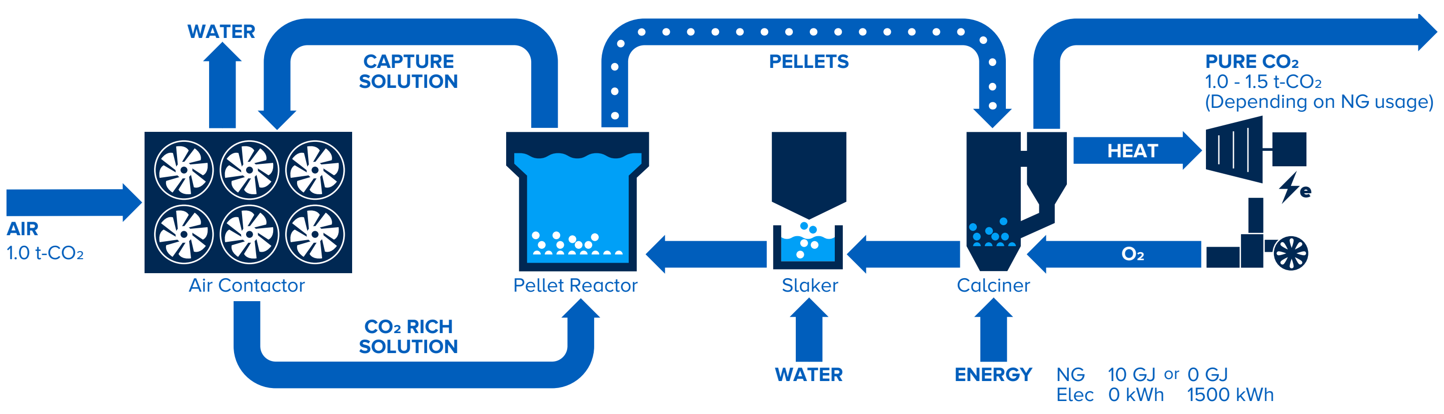
Unlike BECCS, DACCS facilities extract CO_2 directly from atmospheric air. This comes with some key advantages:

- Capture plants can be co-located with storage locations, reducing transport costs
- Plants may be deployed in windy locations reducing the costs of operating fans
- Plants can be located where they have access to renewable electricity.

Capture of CO_2 from the atmosphere is more difficult than capturing it from other sources because atmospheric CO_2 is very dilute at approximately 400 parts per million. This is just one percent of the CO_2 concentration in flue gas from a gas-fired power station. The energy requirements for concentrating CO_2 from such low levels are considerably higher than those from more concentrated sources.

A pilot CO_2 capture and utilisation plant at Twence Waste-to-Energy plant. Image courtesy of Twence.

Carbon Engineering's pilot plant Direct Air Capture system. Shown are the air contactors and calciner (left). Image courtesy of Carbon Engineering Ltd.



CE'S DIRECT AIR CAPTURE PROCESS, SHOWING THE MAJOR UNIT OPERATIONS - AIR CONTACTOR, PELLET REACTOR, SLAKER AND CALCINER – WHICH COLLECTIVELY CAPTURE, PURIFY AND COMPRESS ATMOSPHERIC CO_2

FIGURE 23 CARBON ENGINEERING'S DIRECT AIR CAPTURE AND STORAGE TECHNOLOGY

Carbon Engineering of Canada has developed a DAC technology that absorbs atmospheric CO_2 using a liquid potassium hydroxide (KOH) solution. A chemical reaction traps the CO_2 as a carbonate salt. The salt is extracted in pellet form and calcined (heated to separate CO_2) to release pure CO_2. Energy to drive the process is provided either from externally supplied renewable electricity or natural gas firing. If natural gas is used, the CO_2 from firing is captured within the process for storage, resulting in net-negative emissions. The plant can flexibly operate on any combination of electricity or natural gas. Figure 23 above shows how the Carbon Engineering process works[86].

Carbon Engineering claims a capture cost as low as US $150 per tonne including geological storage, based on engineering analysis[87]. This cost assumes large-scale deployment (one Mt per year capacity).

Oxy Low-Carbon Ventures, a subsidiary of Occidental, has announced a new venture called 1PointFive which plans to build commercial-scale DAC plants, using Carbon Engineering's process[88].

Climeworks of Switzerland and Global Thermostat of the US have taken a different approach to DAC. Their technologies rely on propriety solid adsorbent materials to adsorb CO_2 from incoming air. Once the adsorbent is saturated with CO_2, it is heated to cause CO_2 desorption. This is a form of a temperature swing adsorption (TSA) process. TSA has a long history of industrial use, but this is its first DAC application. Their TSA process also captures considerable volumes of water from the atmosphere, making clean water a useful co-product.

Climeworks has opened several small-scale commercial facilities capturing atmospheric CO_2:

- Providing CO_2 for a greenhouse (displacing fossil-fuel based CO_2)
- For storage with a geothermal power station's reinjected water
- For conversion of power to synthetic zero-emissions methane.

Global Thermostat demonstrated their technology in a pilot plant with a capacity of 4000 tonnes of CO_2 per year and has now partnered with ExxonMobil to scale it up.

Rendering showing 'first look' of what will be the world's largest DAC plant, currently being engineered by Carbon Engineering and 1PointFive. Image courtesy of Carbon Engineering Ltd.

5.6 CCS INNOVATION

MODULARISATION

Like all industrial technologies, unit costs for CCS are heavily influenced by economies of scale. This means that as the capacity (tonnes per year) of a CCS facility increases, the costs of capture go down. Economies of scale favour deployment in larger-scale applications like gas processing plants which have large tonnages of CO_2 available for capture each year. However, not all sectors produce this much CO_2.

The growth and spread of CCS means that there is increasing demand for more economical carbon capture plants that can operate at ever smaller scales without incurring a significant penalty for their smaller size. This is where modularisation comes in. Modular plants are those built in a standardised way under mass production techniques. Typically, they are manufactured offsite in purpose-built facilities and delivered in discrete, modular components (often in shipping containers).

Modular systems can offset reduced economies of operating scale through increased economies of plant manufacturing scale. Modular carbon capture plants have their costs further reduced through:

- Standardised plant foundations
- Standardised plant designs, including all engineering drawings
- Remote or automated operation
- Modular packaging which greatly reduces on-site construction time and costs.

A significant portion of the world's emissions sources are from smaller scale facilities: pulp and paper plants, WtE facilities, smaller gas-fired power stations, and so on. Modular plants enable economic deployment of carbon capture at these smaller plants.

Norwegian company Aker Carbon Capture's modular product, 'Just Catch', comes in two standardised carbon capture capacities of 40,000 tonnes per year and 100,000 tonnes per year. This absorption-based system uses the same process and S26 amine solvent as Aker Carbon Capture's more mature capture plants. Aker Carbon Capture has been contracted to supply its first Just Catch system at the Twence WtE plant in the Netherlands, scheduled to be delivered late 2021.

Modularisation and containerisation of carbon capture plants are growing trends within the CCS technology sector. Mitsubishi Heavy Industry has referred to the benefits of 'modular construction' as enabling a reduction in construction time and costs by pre-assembling much of the equipment in offsite containers[89].

Small-scale capture plants work best when integrated into CCS hubs – bringing together captured CO_2 from multiple sources for compression, transport and storage. Modularisation will support further development of CCS by enabling smaller CO_2 sources to be economically captured and boosting the scale of nearby hubs.

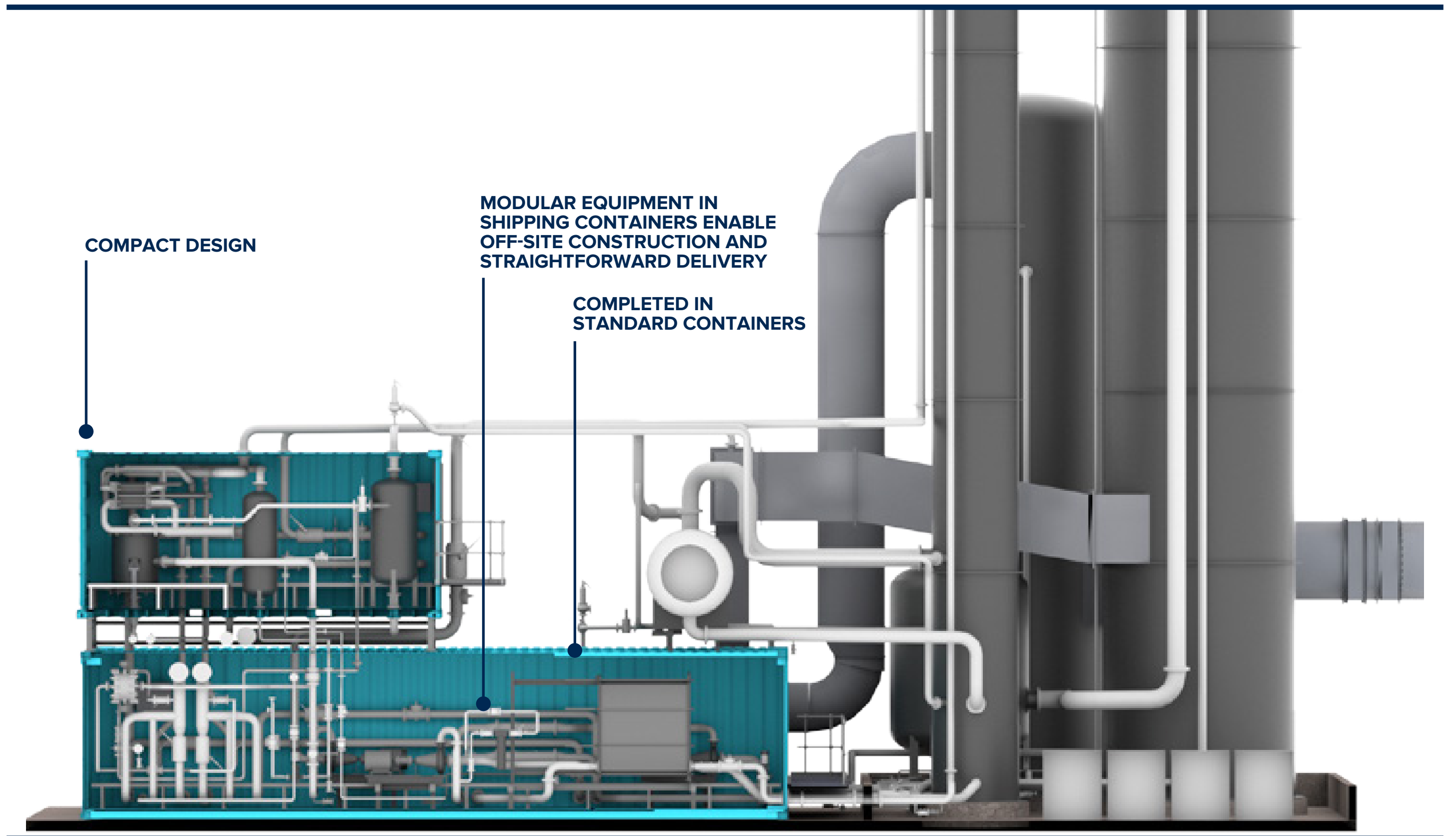


FIGURE 24 AKER 'JUST CATCH' MODULAR CARBON CAPTURE SYSTEM
Image courtesy of Aker Solutions.

METAL ORGANIC FRAMEWORKS

Adsorption based systems (where CO_2 binds to the surface of a solid) have been used for many years in carbon capture and other industrial gas separation applications. Adsorbent solids have typically been manufactured as granular particles, with adsorption occurring in vessels containing packed beds of these particles.

Metal Organic Frameworks (MOFs) are structured, crystalline compounds with highly tuneable adsorption properties, making them promising candidates for developing improved adsorption-based carbon capture processes. Most MOFs are produced at the micro or laboratory scale[90] so manufacturing significant quantities for their industrial deployment is the next challenge.

Carbon capture technology company Svante (formerly Inventys) is developing a test unit for its proprietary MOF adsorbents to use in their rotary rapid temperature swing adsorption process. This will form part of Svante's ongoing CO_2MENT Project demonstrating carbon capture and utilisation at the Lafarge Cement plant in Richmond, Canada.

ADVANCED SOLVENTS

Solvent-based carbon capture systems are the workhorse of the expanding CCS industry. But, traditional monoethanolamine (MEA) and related compounds were developed to remove CO_2 and hydrogen sulphide from natural gas. These amine-based solvents come with problems:

- Degradation is a key challenge, where there is a chemical breakdown of the amine molecules due to reactions with oxygen, SOx and NOx in the flue gas, as well as through thermal breakdown in the solvent stripper. Degradation adds to costs by producing waste solvent which must be disposed of safely. It means continually buying fresh solvent.
- MEA and similar solvents are very good at absorbing CO_2 from flue gas but they require a lot of thermal energy to force CO_2 back out of the solution so the solvent can be reused.
- Corrosion can be an issue in capture plants using MEA.

Advanced solvents are now being developed that address some, or all, of the disadvantages of MEA solvents:

- UK-based Carbon Clean Solutions Ltd (CCSL) has developed a proprietary solvent called APBS which, in conjunction with their improved absorption process, requires 20-40 per cent less heat and power duty than MEA-based systems. Their solvent combines a proprietary blend of advanced amines, alcohols and piperazine compounds. CCSL's testing has shown significantly less degradation of the solvent in plant testing than MEAs[91].
- Mitsubishi Heavy Industry of Japan has also been developing its solvent technology for CO_2 capture in applications such as coal-fired power and chemicals production (urea). They have commercially deployed their 'KS-1' proprietary 'hindered amine' solvent in industrial applications. Although KS-1 is not new – it was originally developed in 1990 – its deployment on an industrial scale represents a step forward for carbon capture.

6.0

APPENDICES

6.1 COMMERCIAL FACILITIES IN OPERATION

FACILITY TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa) (MAX)	CAPTURE TYPE	STORAGE TYPE
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	Operational	United States	1972	Natural gas processing	0.40	Industrial Separation	Enhanced Oil Recovery
Enid Fertilizer	Operational	United States	1982	Fertiliser production	0.20	Industrial Separation	Enhanced Oil Recovery
Shute Creek Gas Processing Plant	Operational	United States	1986	Natural gas processing	7.00	Industrial Separation	Enhanced Oil Recovery
Sleipner CO_2 Storage	Operational	Norway	1996	Natural gas processing	1.00	Industrial Separation	Dedicated Geological Storage
Great Plains Synfuels Plant and Weyburn-Midale	Operational	United States	2000	Synthetic natural gas	3.00	Industrial Separation	Enhanced Oil Recovery
Core Energy CO_2-EOR	Operational	United States	2003	Natural gas processing	0.35	Industrial Separation	Enhanced Oil Recovery
Sinopec Zhongyuan Carbon Capture Utilisation and Storage	Operational	China	2006	Chemical production	0.12	Industrial Separation	Enhanced Oil Recovery
Snøhvit CO_2 Storage	Operational	Norway	2008	Natural gas processing	0.70	Industrial Separation	Dedicated Geological Storage
Arkalon CO_2 Compression Facility	Operational	United States	2009	Ethanol production	0.29	Industrial Separation	Enhanced Oil Recovery
Century Plant	Operational	United States	2010	Natural gas processing	5.00	Industrial Separation	Enhanced Oil Recovery & Gelogical Storage
Bonanza BioEnergy CCUS EOR	Operational	United States	2012	Ethanol production	0.10	Industrial Separation	Enhanced Oil Recovery
PCS Nitrogen	Operational	United States	2013	Fertiliser production	0.30	Industrial Separation	Enhanced Oil Recovery
Petrobras Santos Basin Pre-Salt Oil Field CCS	Operational	Brazil	2013	Natural gas processing	4.60	Industrial Separation	Enhanced Oil Recovery
Lost Cabin Gas Plant	Operation suspended	United States	2013	Natural gas processing	0.90	Industrial Separation	Enhanced Oil Recovery
Coffeyville Gasification Plant	Operational	United States	2013	Fertiliser production	1.00	Industrial Separation	Enhanced Oil Recovery
Air Products Steam Methane Reformer	Operational	United States	2013	Hydrogen production	1.00	Industrial Separation	Enhanced Oil Recovery
Boundary Dam Carbon Capture and Storage	Operational	Canada	2014	Power generation	1.00	Post-combustion capture	Enhanced Oil Recovery
Uthmaniyah CO_2-EOR Demonstration	Operational	Saudi Arabia	2015	Natural gas processing	0.80	Industrial Separation	Enhanced Oil Recovery
Quest	Operational	Canada	2015	Hydrogen Production Oil sands upgrading	1.20	Industrial Separation	Dedicated Geological Storage
Karamay Dunhua Oil Technology CCUS EOR	Operational	China	2015	Chemical production methanol	0.10	Industrial Separation	Enhanced Oil Recovery
Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)	Operational	United Arab Emirates	2016	Iron and steel production	0.80	Industrial Separation	Enhanced Oil Recovery

FACILITY TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa) (MAX)	CAPTURE TYPE	STORAGE TYPE
Petra Nova Carbon Capture	Operation suspended	United States	2017	Power generation	1.40	Post-combustion capture	Enhanced Oil Recovery
Illinois Industrial Carbon Capture and Storage	Operational	United States	2017	Ethanol production – ethanol plant	1.00	Industrial Separation	Dedicated Geological Storage
CNPC Jilin Oil Field CO_2 EOR	Operational	China	2018	Natural gas processing	0.60	Industrial Separation	Enhanced Oil Recovery
Gorgon Carbon Dioxide Injection	Operational	Australia	2019	Natural gas processing	4.00	Industrial Separation	Dedicated Geological Storage
Qatar LNG CCS	Operational	Qatar	2019	Natural gas processing	2.10	Industrial Separation	Enhanced Oil Recovery
Alberta Carbon Trunk Line (ACTL) with Nutrien CO_2 Stream	Operational	Canada	2020	Fertiliser production	0.30	Industrial Separation	Enhanced Oil Recovery
Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream	Operational	Canada	2020	Oil refining	1.40	Industrial Separation	Enhanced Oil Recovery

6.2 COMMERCIAL CCS FACILITIES IN CONSTRUCTION, ADVANCED AND EARLY DEVELOPMENT

FACILITY TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa) (MAX)	CAPTURE TYPE	STORAGE TYPE
Yanchang Integrated Carbon Capture and Storage Demonstration	In Construction	China	Delayed to 2020s	Chemical production	0.41	Industrial Separation	Enhanced Oil Recovery
Sinopec Shengli Power Plant CCS	Early Development	China	2020s	Power generation	1.00	Post-combustion capture	Enhanced Oil Recovery
Acorn Scalable CCS Development	Early Development	United Kingdom	2020s	Oil Refining	4.00	Industrial Separation	Dedicated Geological Storage
Korea-CCS 1 & 2	Early Development	South Korea	2020s	Power generation coal-fired	1.00	Under evaluation	Dedicated Geological Storage
Sinopec Qilu Petrochemical CCS	In Construction	China	2020-2021	Chemical production	0.40	Industrial Separation	Enhanced Oil Recovery
Project Interseqt - Hereford Ethanol Plant	Early Development	United States	2021	Ethanol Production	0.30	Industrial Separation	Dedicated Geological Storage
Project Interseqt - Plainview Ethanol Plant	Early Development	United States	2021	Ethanol Production	0.33	Industrial Separation	Dedicated Geological Storage
Wabash CO_2 Sequestration	Advanced Development	United States	2022	Fertiliser production	1.75	Industrial Separation	Dedicated Geological Storage
San Juan Generating Station Carbon Capture	Advanced Development	United States	2023	Power Generation	6.00	Post-combustion capture	Enhanced Oil Recovery
Santos Cooper Basin CCS Project	Advanced Development	Australia	2023	Natural Gas Processing	1.70	Industrial Separation	Dedicated Geological Storage
Fortum Oslo Varme - Langskip	Advanced Development	Norway	2023-2024	Waste-to-Energy	0.40	Post Combustion Capture	Dedicated Geological Storage
Brevik Norcem - Langskip	Advanced Development	Norway	2023-2024	Cement Production	0.40	Industrial Separation	Dedicated Geological Storage
Hydrogen 2 Magnum (H2M)	Early Development	The Netherlands	2024	Power Generation	2.00	Industrial Separation	Dedicated Geological Storage
Project Pouakai Hydrogen Production with CCS	Early Development	New Zealand	2024	Hydrogen Production and Power Generation	1.00	Industrial Separation	In evaluation
Caledonia Clean Energy	Early Development	United Kingdom	2024	Power generation with potential for co-production of Hydrogen for heat and transport applications	3.00	Post-combustion capture	Dedicated Geological Storage
Cal Capture	Advanced Development	United States	2024	Power Generation	1.40	Post-combustion capture	Enhanced Oil Recovery
Velocys' Bayou Fuels Negative Emission Project	Early Development	United States	2024	Chemical Production	0.50	Industrial Separation	Dedicated Geological Storage
OXY and Carbon Engineering Direct Air Capture and EOR Facility	Early Development	United States	Mid 2020s	Air	1.00	Industrial Separation	Enhanced Oil Recovery
LafargeHolcim Cement Carbon capture	Early Development	United States	Mid 2020s	Cement Production	0.72	Industrial Separation	In Evaluation
HyNet North West	Early Development	United Kingdom	Mid 2020s	Hydrogen Production	1.50	Industrial Separation	Dedicated Geological Storage

FACILITY TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa) (MAX)	CAPTURE TYPE	STORAGE TYPE
Gerald Gentleman Station Carbon Capture	Advanced Development	United States	Mid 2020s	Power Generation	3.80	Post-combustion capture	In Evaluation
Mustang Station of Golden Spread Electric Cooperative Carbon Capture	Advanced Development	United States	Mid 2020s	Power Generation	1.50	Post-combustion capture	In Evaluation
Prairie State Generating Station Carbon Capture	Advanced Development	United States	Mid 2020s	Power Generation	6.00	Post-combustion capture	Dedicated Geological Storage
Plant Daniel Carbon Capture	Advanced Development	United States	Mid 2020s	Power Generation	1.80	Post-combustion capture	Dedicated Geological Storage
Lake Charles Methanol	Advanced Development	United States	2025	Chemical production	4.00	Industrial Separation	Enhanced Oil Recovery
Dry Fork Integrated Commercial Carbon Capture and Storage (CCS)	Early Development	United States	2025	Power Generation	3.00	Post-combustion capture	Dedicated Geological Storage
The Clean Gas Project	Early Development	United Kingdom	2025	Power Generation	6.00	Post-combustion capture	Dedicated Geological Storage
Abu Dhabi CCS Phase 2: Natural gas processing plant	Advanced Development	United Arab Emirates	2025	Natural Gas Processing	2.30	Industrial Separation	Enhanced Oil Recovery
Red Trail Energy BECCS Project	Early Development	United States	2025	Ethanol Production	0.18	Industrial Separation	Dedicated Geological Storage
The Illinois Clean Fuels Project	Early Development	United States	2025	Chemical Production	2.70	Industrial Separation	Dedicated Geological Storage
Clean Energy Systems Carbon Negative Energy Plant - Central Valley	Early Development	United States	2025	Power Generation	0.32	Oxy-combustion Capture	In Evaluation
Project Tundra	Advanced Development	United States	2025-2026	Power Generation	3.60	Post-combustion capture	Dedicated Geological Storage
Northern Gas Network H21 North of England	Early Development	United Kingdom	2026	Hydrogen Production	1.50	Industrial Separation	Dedicated Geological Storage
Hydrogen to Humber Saltend	Early Development	United Kingdom	2026-2027	Hydrogen Production	1.40	Industrial Separation	Dedicated Geological Storage
Drax BECCS Project	Early Development	United Kingdom	2027	Power Generation	4.00	Industrial Separation	In evaluation
Ervia Cork CCS	Early Development	Ireland	2028	Power generation and Oil Refinery	2.50	Industrial Separation	Dedicated Geological Storage
The ZEROS Project	In Construction	United States	Late 2020s	Power Generation (Waste to Energy)	1.50	Oxy-fuel combustion capture	Enhanced Oil Recovery

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ENDNOTES

i. 70Mtpa of pure H_2 is currently produced. Approximately another 50Mtpa of H_2 mixed with CO in syngas is also produced.

ii. Scope one, two and three greenhouse gas emissions' definitions, taken from Australian Government Clean Energy Regulator http://www.cleanenergyregulator.gov.au/NGER/About-the-National-Greenhouse-and-Energy-Reporting-scheme/Greenhouse-gases-and-energy:

Scope 1 emissions: Emissions released to the atmosphere as a direct result of an activity, or series of activities at a facility level; sometimes referred to as direct emissions.

Scope 2 emissions: Emissions released to the atmosphere from the indirect consumption of an energy commodity, e.g. 'indirect emissions' come from the use of electricity produced by the burning of coal in another facility.

Scope 3 emissions: Indirect emissions other than scope 2 emissions that are generated in the wider economy. They occur as a consequence of the activities of a facility, but from sources not owned or controlled by that facility's business.

iii. Historic data has been adjusted to align it with the new facility classification system. This does not include two facilities that completed operations and closed.

iv. Policy paper, UK Budget 2020 available at www.gov.uk

v. The IPO prospectus published by Saudi Aramco in November 2019 stressed its low carbon product footprint as a key mitigation measure against climate-related risks. A competitive ranking appears on p. 83.

vi. Based on a commissioned evaluation from Qamar Energy, June 2019.

vii. Available at https://www.cceguide.org/guide/

viii. Global CCS Institute analysis of IEA data.

ix. CO_2e emissions 51.53 kg CO_2e/GJ, Polymer Electrolyte Membrane (PEM) efficiency of conversion of electricity to hydrogen (71 per cent).

x. Assumes 2Mtpa CO_2, 50km, 250mm pipeline, six per cent cost of capital, compression from 1bar to 150 bar, electricity price of USD80/MWh, USD3/tCO_2 for storage and MMV, 30 year asset life.

xi. Without a carbon price.

FIGURES, TABLES & CHARTS

FIGURE 1

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FIGURE 3

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FIGURE 9

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Find Out More

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Any Questions

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