GLOBAL STATUS OF CCS 2019

TARGETING CLIMATE CHANGE
URGENT ACTION IS REQUIRED TO ACHIEVE CLIMATE CHANGE TARGETS. CARBON CAPTURE AND STORAGE IS VITAL.
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 almost 40 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 2019 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.

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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
ETS Emissions Trading Scheme
EU ETS European Union’s Emissions Trading System
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
Mtpa Million Metric Tonnes Per Annum
MW Megawatt
NDC Nationally Determined Contribution
OECD Organisation for Economic Co-operation and Development
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

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As if the world needed any more evidence that the effects of climate change are with us now and getting worse, 2019 bore witness to unprecedented catastrophic events that go well beyond weather variability and cannot be explained away as simply extreme events that happen from time-to-time. Fires of devastating proportion and impact – in many cases more severe and widespread than ever previously experienced – have wrought havoc in countries as disparate as the United States (US), France, Greece, Portugal and Australia. Elsewhere, extreme storm events have been experienced. Think Typhoon Hagibis in Japan during the Rugby World Cup, prolonged monsoons in India, Hurricane Dorian in the Bahamas and Typhoon Lekima in China to name but a few, all with devastating loss of life and property. Meanwhile droughts worsen and deepen in many parts of the world, including in essential food production areas.

The climate science has been clear for many years. Now we are experiencing first hand the impacts of unabated greenhouse gas emissions.

Time is not on our side to achieve the necessary targets. As this report reveals, positive policy intentions and actions. It is possible to get there but it requires policies that mobilise enormous sums of capital to deliver an unprecedented transformation of the global energy system. It is hard but it can be done.

The recurring theme of many deeply analytical and credible reports is that we need all technologies to win this wrestle. We can no longer afford to have confected competitions between technologies with prejudices that serve to compromise our ability to rapidly reduce emissions.

Against this background we have seen exciting new developments in the energy transformation during 2019. For the second year in a row the CCS facility pipeline has grown. The flexibility, applicability and increasingly positive economics of applying CCS to a range of emission sources is coming to the fore. As this report reveals, positive policy intentions and settings are apparent in many parts of the world and especially the US, the UK, Norway and the Netherlands leading to more projects being added to our globally comprehensive database. CCS is also to the fore in the plans and policies of the EU while Japan continues to make impressive strides forward. It is also notable that China continues to attach importance to CCS and has established a new professional committee to broaden the advice and support to government on CCS policy and actions.

2019 will also be celebrated for the commencement of injection at the world’s largest geological storage facility – Gorgon – offshore NW Western Australia. Ramping up over time to capture and store between 3.4 and 4.0 million tonnes of CO2 per annum, Gorgon puts Australia on the CCS facility map and is a credit to the determination and persistence of the joint venture partners led by Chevron and including prominent Institute members Shell and Exxon Mobil.

Hydrogen as a vital new energy source in the decarbonisation race was also to the fore in 2019. In Europe, Australia, Japan, South Korea and an increasing number of other countries, hydrogen is receiving policy attention not seen for several decades. The difference this time around is that the need for a zero-emission energy dense fuel is vital and the technology to produce and deliver the hydrogen has advanced substantially in the intervening period. As is noted later in this report, the most technologically proven, economical, at-scale process for producing clean hydrogen is through steam methane reforming or coal gasification, both with CCS. The potential market for clean hydrogen is substantial and early stage investment in production facilities, evidenced for example in the Japanese/Australian joint venture of building a coal gasification pilot plant, is the harbinger of a growing industry as are plans in the UK and in Europe.

Perhaps the most compelling development in the last 12 months though is that increasingly, CCS is the stand out technology to genuinely deliver a just transition for many fossil fuel-based communities. Dealing with the associated emissions for extracting, processing and using fossil fuels and perhaps more significantly developing the new energy economy based on clean fuels like hydrogen, is dependent on CCS deployment. And as CCS is deployed, many communities that otherwise may have a less prosperous outlook in a carbon-constrained world become a positive part of the transition.

But we have much more work to do. Few clean energy technologies are on track to be deployed at the scale required to meet the Paris climate targets. CCS is resurgent but still lagging while emissions again rose required to meet the Paris climate targets. CCS is resurgent but still lagging while emissions again rose in the past year. Now is the time to rally for greater policy support and for capital to be allocated to build on the positive CCS progress of the past two years.
The effects of climate change are already raging across the world with wild fires, droughts, and rising sea levels. Bad as it is already, we risk far worse. Failure to mitigate climate change is deeply dangerous; we owe it to future generations to tackle this global and urgent problem. The faster we can reduce emissions in the near-term, the better our chance of preventing the worst impacts of climate change.

For this, we need to change the way we think about this global challenge. Turning towards a new form of sustainable economic growth and looking at investment in innovation would also yield strong societal and economic returns. The Global Commission on the Economy and Climate has shown that bold climate action could deliver returns of trillions of dollars per year in the period to 2030 and create more than 60 million good jobs. We need to invest in all opportunities for emissions reductions while radically changing how we work, live, and consume. Living and consuming more efficiently is the first step, along with a massive growth in renewable and clean energy. Yet, we must not forget that we will need to completely transform the economy so that it becomes carbon neutral and deploy a portfolio of measures and technology solutions to accelerate the clean energy transition.

One of the opportunities that we have at hand, carbon capture, use and storage, will play a vital role as indicated by the Intergovernmental Panel on Climate Change’s report on Global Warming of 1.5°C. The diversity of its applications is immense; from direct air capture delivering negative emissions, to the ability to prevent infrastructure emissions lock-ins by abating existing infrastructure in the industrial and power sectors, capturing, using and storing carbon will be a vital instrument in reaching net-zero emissions goals.

As is the case for many abatement options, effective actions and policy to accelerate the deployment of a wide-range of carbon capture use and storage technologies across many sectors of the economy, and especially those that are hard to decarbonise, are urgently needed.

As a society, we have a responsibility towards future generations to mitigate climate change. Investment in mitigation and innovation will undoubtedly offer large returns and great value, while improving our ability to tackle climate change through sustained action. Time is short, but we have in our hands a different model of development. It is the sustainable and inclusive growth story of the 21st century.
Together, we are all part of the human species. Separating us are just divisions of our own making – such as religious beliefs, borders drawn on maps, concepts of race, money, and gender.

Debates about saving our planet from global warming are misplaced. Planet Earth doesn’t need saving - it will recover long after we have wiped ourselves and all other life out - this is about the survival of the human species. But... what if? What if we could focus more on this great threat to humanity and why we need to work together, rather than focus on what spreads us apart?

If we can make this shift, we could learn to relate as one great tribe of humans, learn to respect our common home, and ultimately save the future of all life on Earth, including our own.

At just 18, I am no expert on the science of global warming, but I am likely the only person on the planet of my generation to have the privilege of first-hand experience in Earth’s three main polar regions. Journeys that saw me cover a total of around 1,300km in 80 days.

I now feel a deep emotional connection with our planet Earth and a responsibility to play my part in the protection of these incredibly beautiful and fragile environments.

My polar expeditions confirmed for me that global warming is an undeniable truth. That is why I call on the political and business leaders to stop arguing and start taking massive action. It’s not about choosing the best technology – it’s about supporting ALL viable technologies and ideas, including carbon capture and storage – that together create a web that seeks to hold global temperature rise to under two degrees Celsius (if that is even still possible).

My generation will inherit this great threat of global warming and the political decisions of today’s leaders. Please give us a platform from which we can still achieve a positive outcome. I am confident that my generation will have the technology, the passion and the unified movement to make a meaningful difference, but it is up to current world leaders to make sure we still have a fighting chance.

Please, give us that fighting chance.

JADE HAMEISTER OAM
Polar explorer
I often hear that lower cost solar and wind power along with the emerging breakthroughs in energy storage mean that these sources will be enough to get us to a carbon-free power grid. But because the world must balance the need to eliminate carbon emissions with economic growth, we should also consider what solutions would be most affordable. A recent study from researchers at MIT found that supporting renewable energy with a mix of clean energy solutions—including nuclear and carbon capture and storage (CCS)—would make carbon-free electricity up to 62 percent cheaper than using renewables alone.

Another way we can get zero-carbon electricity is carbon capture, utilisation, and storage, which separates and permanently stores CO2 pollution from an energy plant’s exhaust to keep it out of the atmosphere. This technology is especially important in places where there isn’t good renewable energy potential, or where it would be too costly to retire and replace existing power plants.
progress in curbing emissions has been slow. Approximately 80 per cent and the rapid take-up of renewable energy over the past 20 years, Despite both the urgent need for action to mitigate climate change, CCS IS VITAL TO ACHIEVE CLIMATE CHANGE TARGETS

Despite both the urgent need for action to mitigate climate change, and the rapid take-up of renewable energy over the past 20 years, progress in curbing emissions has been slow. Approximately 80 per cent of primary energy is supplied by fossil fuels, the same as 50 years ago. Global energy-related CO2 emissions are on an upward trend again—having temporarily stabilised for a few years, they rose by 1.7 per cent in 2018. Government commitments do not bridge the gap between current emissions levels and those consistent with limiting global temperature rise to 1.5°C. The time available to limit temperature rises to 1.5°C is running out. The Special Report on Global warming of 1.5°C (IPCC SR15) reinforced the important role of CCS in avoiding dangerous climate change. It underlined that reducing emissions alone is no longer enough. To limit global temperature rise to 1.5°C above pre-industrial levels, the world must reach net zero emissions by around 2050. Most modelling scenarios show that this will require significant deployment of negative emissions technologies. Bioenergy with CCS (BECCS) is one of the few available that can deliver to the necessary scale. The deployment of CCS is not happening quickly enough for it to play its role in meeting emissions reductions targets at the lowest possible cost. The IEA’s ‘Tracking Clean Energy’ progress indicator, provides a status snapshot of 39 critical energy technologies needed to meet a less than 2°C target under its Sustainable Development Scenario (SDS). Only seven of the technologies assessed are “on-track”. Crucially CCS in power, and in industry and transformation, are “off-track”. To achieve the levels outlined in the SDS, the number of industrial scale facilities needs to increase a hundredfold, from 19 in operation now to more than 2,000 by 2040. CCS IS A PROVEN AND WELL UNDERSTOOD TECHNOLOGY

CCS prevents carbon dioxide (CO2) from being released into the atmosphere. The technology involves capturing CO2 produced by large industrial plants, compressing it for transportation and then injecting it deep into a rock formation at a carefully selected and safe site, where it is permanently stored. CCS is proven and well understood. Since the 1930s, carbon capture equipment has been used commercially to purify natural gas, hydrogen and other gas streams in industrial settings. CO2 was first injected underground in commercial-scale operations in 1972. Over 260 million tonnes (Mt) of CO2 emissions from human activity (anthropogenic sources) has already been captured and stored. The global capture and storage capacity of projects currently operating or under construction, stands at around 40 million tonnes per annum (Mtpa). CCS reduces emissions from industrial processes vital to the global economy; like steel, cement and chemicals production. Paired with bioenergy used for power generation or biofuel production, it is one of few technologies that can deliver negative emissions on a large enough scale to limit temperature rises to 1.5°C. It can be applied to coal and gas fired power plants to help provide low emissions generation capacity, complementing increased use of intermittent renewables; and in the production of low carbon hydrogen for fuel, heat and transport. THE NEED FOR AND BENEFIT FROM URGENT ACTION

The IEA’s World Energy Outlook 2019 describes the measures necessary to deliver its Sustainable Development Scenario (SDS), a future where the United Nations energy related sustainable development goals for emissions, energy access and air quality are met. This scenario is consistent with a 66 per cent probability of limiting global temperature rise to 1.5°C. As shown in Figure 1 under this scenario: • The mass of CO2 captured and permanently stored in 2050 is 1.5 billion tonnes per annum • The average mass of CO2 captured and permanently stored each year between 2019 and 2050 is 1.5 billion tonnes per annum • The mass of CO2 captured and permanently stored in 2050 reaches 2.8 billion tonnes per annum • The mass of CO2 captured is split almost equally between the power sector and industry sectors including iron and steel production, cement production, refineries and upstream oil and gas production. The deployment of CCS is not happening quickly enough for it to play its role in meeting emissions reductions targets at the lowest possible cost. The IEA’s “Tracking Clean Energy” progress indicator, provides a status snapshot of 39 critical energy technologies needed to meet a less than 2°C target under its Sustainable Development Scenario (SDS). Only seven of the technologies assessed are “on-track”. Crucially CCS in power, and in industry and transformation, are “off-track”. To achieve the levels outlined in the SDS, the number of industrial scale facilities needs to increase a hundredfold, from 19 in operation now to more than 2,000 by 2040. To rapidly scale up the technology in a smooth and steady way, urgent action is required. Governments have a pivotal role to play, by providing a clear, stable and supportive policy framework for CCS. The good news is that CCS provides a wealth of benefits in addition to its primary role in reducing emissions. It enables a just transition to new low emissions industries for communities currently reliant on emissions intense employment. It can protect people from the severe economic and social disruption that otherwise results from closing local industries. On top of this, CCS: • supports high paying jobs; • reduces total system costs of electricity supply by providing reliable, dispatchable generation capacity when fitted on flexible fossil fuel power plants; • can utilise existing infrastructure that would otherwise be decommissioned, helping to defer shut-down costs; and • provides knowledge spillovers that can support innovation-based economic growth. The time available to limit temperature rise to 1.5°C is running out. Widespread use of CCS technology is critical to meeting these goals. We need to scale up deployment now. 11 12
CLOSING THE AMBITION GAP AND GETTING ON WITH THE INEVITABLE

When I was a teenager growing up in Northern California, we had a big wildfire every 10 years or so. Shockingly, thousands of homes would be lost and many more people displaced. Now huge wildfires happen every year. As I write this, one hundred kilometers north, 77,000 acres are burning, casting a haze of smoke across the state. These once-rare and extreme events like wildfires, floods, droughts, extreme heat, and intense hurricanes happen much more frequently now, with enormous societal cost and personal suffering. Climate change is no longer abstract or something we need to worry about in the future. I am worried now.

Over the last 20 years, the role of carbon capture and storage has evolved from “nice to have” to “necessary,” and now, CCUS is inevitable. We need Gt* scale CCUS now. We are using up our carbon budget so quickly, that at some point in the not-to-distant future we are likely to begin scrubbing carbon dioxide from the atmosphere. But this is much less efficient than capturing CO₂ directly from point sources. So why aren’t we doing more to scale up CCUS from point sources when we could stop these emissions now?

Of course, there are many reasons why we aren’t doing more. At the top of the list is lack of the carrots or sticks that would motivate action and justify the investment. But perhaps even more important than this, we have an ambition gap between the rate that CCUS is growing today – about 10 per cent a year, compared to the rate needed to reach a Gt/year by 2040. If we could just double scaleup rate to 20 per cent per year, and sustain that to 2040, bingo, we reach 1 Gt/year by 2040. Let’s do it.

* Billion tons of CO₂ captured and stored per annum
3.0 GLOBAL STATUS OF CCS
Over the past year the global development and deployment of CCS continued to gather pace. The world map on these pages shows the growing presence of CCS around the globe. In 2019, the number of large-scale CCS facilities increased to 51.

Of these:
- 19 are operating;
- four are under construction;
- 10 are in advanced development using a dedicated front end engineering design (FEED) approach; and
- 18 are in early development.

Right now, those in operation and construction have the capacity to capture and permanently store around 40 million tonnes of CO₂ every year. This is expected to increase by about one million tonnes in the next 12-18 months. In addition, there are 39 pilot and demonstration scale CCS facilities (operating or about to be commissioned) and nine CCS technology test centres.

**MAJOR STRIDES IN 2019 FOR CCS**

In 2019, more than 25 million tonnes of CO₂ from the power and industrial sectors was permanently stored using CCS. Two new facilities commenced operation and others reported the achievement of significant cumulative CO₂ storage milestones:

- CO₂ injection commenced at the Gorgon natural gas processing plant on Barrow Island off the coast of Western Australia in August 2019. This will be the world’s largest dedicated geological CO₂ storage facility when it ramps up to full capacity storing up to 4.0 Mtpa CO₂ a year.
- The Alberta Carbon Trunk Line (ACTL), a 240-kilometre CO₂ pipeline, expected to come online in 2020, will offer CO₂ transport services to industry in Alberta, Canada. North West Redwater Partnership’s Sturgeon refinery and the Agrium fertiliser plant will jointly supply around 1.6 Mtpa of CO₂ via the pipeline to EOR operations in central Alberta.
- 100 million tonnes – Shute Creek gas processing plant in Wyoming US, with a 7 Mtpa CO₂ capture capacity, has cumulatively captured more than 100 million tonnes of CO₂ from natural gas processing operations for use in enhanced oil recovery.
- 38 million tonnes – Great Plains Synfuels plant in North Dakota US, captures CO₂ from the coal (lignite) gasification process, producing syngas (hydrogen and carbon monoxide) for energy use and chemical production. It has delivered around 38 million tonnes of CO₂ for EOR in the Weyburn and Midale fields in Canada since it commenced operation since 2000.
- 22 million tonnes – On the Norwegian continental shelf, Sleipner CO₂ storage and Snøhvit CO₂ storage facilities have cumulatively captured and stored around 22 million tonnes of CO₂. Sleipner was the world’s first large scale dedicated CO₂ geological storage facility, storing CO₂ from natural gas processing since 1996.
- 10 million tonnes – Petrobras Santos Basin CO₂-EOR facility in offshore Brazil, reached a milestone of 10 million tonnes of CO₂ captured and reinjected in the natural gas processing industry. Petrobras is continually expanding the capacity of its floating production storage and offloading (FPSO) units, aiming to cumulatively reinject more than 40 million tonnes of CO₂ by 2025.
3.0 Global Status of CCS
3.1 Global CCS Facilities Update

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FIGURE 3 POWER AND INDUSTRIAL APPLICATIONS OF LARGE-SCALE CCS FACILITIES IN OPERATION, UNDER CONSTRUCTION AND IN ADVANCED DEVELOPMENT

- 5 million tonnes – Air Products’ carbon capture plant on hydrogen in Port Arthur, US, has mitigated more than 5 million tonnes of CO2 by coupling steam methane reforming (SMR) with CCS and has been in operation since 2013.11
- 4 million tonnes – The Quest CCS facility in Canada, operating since the end of 2015, has been capturing CO2 from the SMR process for hydrogen production. Shell Canada announced that 4 million tonnes of CO2 had been captured and safely stored, ahead of schedule.10
- 3 million tonnes – Boundary Dam CCS, the first large-scale CCS facility in power generation, for Boundary Dam Unit 3 in Canada, has been capturing CO2 from the SMR process for hydrogen production. Shell Canada announced that 3 million tonnes of CO2 had been captured and safely stored, ahead of schedule.10

Dry Fork integrated commercial CCS
The Basin Electric Power Cooperative aims to capture 3.0 Mtpa CO2 from the 385 MW Dry Fork coal-fired power station in Wyoming, USA. They are targeting adjacent geological storage formations currently being studied by Wyoming CarbonSAFE.11 The Cooperative is also considering EOR as a potential CO2 storage pathway, utilising nearby CO2 pipeline networks and EOR operations.

CarbonSAFE Illinois hub – Macoupin County
Building on learnings from Illinois Industrial CCS facility in the Archer Daniels Midland Ethanol plant, this project seeks to establish a 50+ million tonne commercial geological storage hub in Illinois USA. Adjacent power plants, such as Prairie State Generation (816 MWe, coal fired power plant, 10 Mtpa CO2) which has been awarded a full-scale FEED study13, and regional ethanol plants are potential CO2 sources.

Integrated mid-continent stacked carbon storage hub
Storage infrastructure would be established in southwestern Nebraska and southwestern Kansas to enable collection of CO2 from ethanol plants, power plants and refineries in the region. Ethanol plants producing 1.9-5 Mtpa CO2 in the region could utilise this infrastructure. The Nebraska Public Power District’s Gerald Gentlemen Station (coal fired) is another potential source of CO2 for this storage hub. A FEED study on the retrofit of Ion Engineering’s non-aqueous ICE-21 solvent capture technology to the Gerald Gentlemen Station is underway.14

FIGURE 4 PIPELINE OF LARGE-SCALE CCS FACILITIES FROM 2010 TO 2019: CO2 CAPTURE AND STORAGE CAPACITY

The CCS pipeline is replenishing, but not fast enough
Figure 4 (below) shows how the CCS facility pipeline has developed over the past decade. It shows a continuous increase in the number of facilities in the pipeline between 2010 and 2017 followed by year-on-year increases in 2018 and 2019. There are many possible explanations for this pattern and it is not possible to be definitive about the causes. However it is likely that the Global Financial Crisis (GFC) which started in mid-2007 and ran through 2009 contributed to the observed decline. The uncertainty in global markets and the economic downturn that accompanied the GFC focused governments’ attention on short-term economic recovery and focussed the private sector on survival. Action to mitigate climate change fell down the list of priorities and both public policy and private capital responded in-kind. Investment in CCS, which requires strong policy and significant capital, subsequently retreated. If data for 2007 to 2009 showed a peak in the project pipeline, that would lend weight to this hypothesis. However, this period was prior to the 2009 establishment of the Institute and the data therefore is unavailable.

The CCS industry has been regaining momentum since 2017 and there are roughly four times as many large-scale CCS facilities operating today as there was in 2010. A number of factors have probably driven the increase in CCS project development observed in 2018 and 2019. The 2015 Paris Agreement established a clear level of ambition to limit global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. This was supported by almost every nation of the world. This agreement refocussed governments, the private sector and civil society on climate mitigation. This has supported examples of stronger climate policy from government (e.g. legislating net-zero emission targets), greater pressure from shareholders on...
Hubs and clusters significantly reduce the unit cost of CO₂ storage through economies of scale, and offer commercial synergies that reduce the risk of investment.

**Key characteristics of hubs and clusters:**
- Multiple industrial point sources of CO₂ connected to a CO₂ transport and storage network.
- Access to large geological storage resources with the capacity to store CO₂ from industrial sources for decades.
- Studies of almost all potential hubs and clusters have been supported by governments.
- Economies of scale deliver lower unit-costs for CO₂ storage.
- Synergies between multiple CO₂ sources and the storage operator reduce cross chain risks and support commercial viability.

**More information about some of these hubs and clusters:**
- Petrobras Santos Basin CCS network was the first “CCS hub and cluster” in operation. It has a unique set up with 10 FPSOs anchored in the Santos Basin off the coast of Rio de Janeiro, Brazil. The captured CO₂ is directly injected into the Lula, Sapinhoá and Lapa oil fields for EOR.
- Supported by CAD445 million from the Alberta Government, the ACTL will transport up to 14.6 Mtpa CO₂ from Alberta’s Industrial Heartland for CO₂ emission reduction. This is in addition to CO₂ transport from the Sturgeon refinery and Agrium fertiliser plant.
- Northern Lights is an open-access CO₂ transport and storage hub, seeking to provide capacity for large CO₂ volumes across Europe. This will move the operation beyond the current Norway full chain CCS facility from the Norecorm and Forum capture sites.
- Six of eight new facilities which emerged in the US are part of the United States Department of Energy’s Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative. This is focused on the development of a geologic storage complex for 50 plus million tonnes of CO₂ from industrial sources.
- CarbonNet is a CO₂ transport and storage hub supported by the Victorian and Australian Governments. It will provide CO₂ transport and storage services to potential capture projects in Australia’s Latrobe Valley. The Hydrogen Energy Supply Chain (HESC) project is constructing a pilot hydrogen production plant via coal gasification and will demonstrate the transport of hydrogen by ship to Japan. A decision on investment on a commercial hydrogen production plant with CCS is expected around 2025. If it proceeds, this plant could be the first customer of the CarbonNet CO₂ hubs.
- Net Zero Teesside in the UK is a CO₂ transport and storage hub for the Tees Valley.
- Other CCS hubs and clusters supported as Projects of Common Interest include Acorn Full Scale CCS, Ervia Cork, the Port of Rotterdam CCUS Backbone Initiative (PORTHOS) and the Amsterdam IJmuiden-CO₂ Transport Hub and Offshore Storage (ATHOS).
- The Net Zero Teesside, Northern Lights, PORTHOS, Xinjiang Junggar CCS hub and the Gulf of Mexico CCS hubs have been selected as kickstarters for the Oil and Gas Climate Initiative’s large-scale investment in CCS hubs and clusters.

**Next wave of CCS: Hubs and clusters**

“Next wave” facilities based around CCS hubs and clusters have featured in 2019. Added to the Global CCS Institute’s database in 2016, these facilities take advantage of the fact that many emissions-intensive facilities (both power and industrial) tend to be concentrated in the same areas. Hubs and clusters significantly reduce the unit cost of CO₂ storage through economies of scale, and offer commercial synergies that reduce the risk of investment. They can play a strategically important role in climate change mitigation.

Figure 5 (opposite) shows CCS hubs and clusters identified as having made significant developments in 2019, and summarises some of the features they share.
To meet climate change mitigation targets, an estimated 2000-plus large scale CCS facilities must be deployed by 2040, requiring hundreds of billions of dollars in investment. Today, there are 19 large scale facilities in operation and four under construction. Figure 6 shows that the business case for investment in each facility was underpinned by favourable commercial conditions and supportive policy. It demonstrates that the private sector will invest in CCS when the right incentives are in place.

3.2 POLICY LEVERS FOR ACCELERATING DEPLOYMENT

Like all large infrastructure projects, the development and construction of CCS facilities is capital intensive. This influences the viability of projects and prices out potential investors. However, learning rates drive costs down as successive CCS facilities come online. For example, assuming a conservative learning rate of 8% per annum from Figure 7 (above), as facilities increase from tens to thousands by mid-century, the cost of capturing CO2 falls by approximately half. It is imperative that investors are incentivised as much as possible in the early stages, to accelerate the learning rate and attract new projects.

There is strong evidence that capture costs have already reduced. Figure 8 (below) shows estimated costs from a range of feasibility and front end engineering and design (FEED) studies for coal combustion CCS facilities using mature amine-based capture systems. Two of the projects, Boundary Dam and Petra Nova are operating today. The cost of capture reduced from over USD100 per tonne CO2 at the Boundary Dam facility to below USD65 per tonne CO2 for the Petra Nova facility, some three years later. The most recent studies show capture costs (also using mature amine-based capture systems) for facilities that plan to commence operation in 2024-28, cluster around USD43 per tonne of CO2. New technologies at pilot plant scale promise capture costs around USD33 per tonne of CO2.
The most obvious way to create incentives for investors is to place a material value on CO₂. Policymakers can choose from options like tax credits, carbon tax or direct regulation as a condition of approval. The mistaken idea that CCS is too expensive compared to other climate change mitigation technologies is easily dispelled when a low value is placed on carbon. For example, the IEA has estimated that as much as 450 MtCO₂ could be captured, utilised and stored annually at a low value is placed on carbon. For example, the IEA has estimated that as much as 450 MtCO₂ could be captured, utilised and stored annually with a global climate action level as low as US$40 per tonne of CO₂ by deploying CCS on the many low-cost opportunities available.

3.0 Global Status of CCS

3.1 Policy Levers for Accelerating Deployment

Figure 9 below shows how government policy and confidence in CCS can reduce the cost of debt over time. Initial CCS facilities are developed under high-risk conditions, due to the existence of weak policy frameworks and few CCS facilities being in operation, so the cost of debt is at its highest.

As more facilities enter operation, and better policy frameworks evolve, the cost of debt is reduced. Eventually a low risk lending rate, representative of a mature industry, is reached.

To explore further detail on policy priorities for policymakers and how to stimulate investment in CCS, download our 2019 Thought Leadership Report Policy priorities to incentivise large scale deployment of CCS at globalccsinstitute.com.

ESG AND DIRECTORS’ DUTIES

A company’s attitude towards environmental, social and corporate governance (ESG) factors, is an increasingly significant consideration for investors, shareholders and the wider public. There is closer scrutiny and reporting of ESG factors that are material to a business’s core activities. While companies are increasingly willing to adopt more sustainable practices, their openness has also been driven by the rise of socially-conscious investment, the concept of the ‘enlightened shareholder’ and increased public activism surrounding environmental, social and governance issues.

In recent years, the ‘environmental’ aspects of corporate governance have increased in importance, with climate change and carbon risk exposure becoming the most pressing considerations. In organisations with a significant CO₂ footprint, investors and shareholders are offered detailed information about matters like exposure to climate change impacts and carbon risk, how these will be adapted to, strategies for addressing greenhouse gas and any new commercial opportunities that have been identified to reduce the business impacts.

Reporting against sustainability and environmental performance measures has moved from being largely voluntary to necessary.

Table 9.1 provides a high-level overview of countries that have policies in place to incentivise CCS deployment.

ESG disclosures and investment decisions are increasingly part of financial reporting obligations. Some suggest there is now a clear link between a company’s ESG performance and its ability to leverage capital, including the cost of that capital. Experience shows that failure to adopt a pragmatic approach to environmental performance and climate change impacts, may result in direct and indirect risks for a company. The burgeoning divestment movement is one example, where the views of shareholders and the wider public have been made very clear to companies perceived as high CO₂ emitters, or failing to address their carbon footprint.

Potential harm to a company’s reputation is an important consideration, but there may be more significant implications for organisations that don’t meet expectations in regard to climate change mitigation. In recent years, resolutions have been brought against corporations by shareholder groups seeking to ensure that companies adapt their practices to the realities of a carbon constrained future. In some instances, shareholders even brought formal legal proceedings against company directors.

And low-carbon technologies will be an important solution for many organisations seeking to address public and investor-led perceptions of their activities, and meet shareholder challenges.

CCS offers a potent opportunity for those with significant CO₂ exposure, to demonstrate their management of the issue and improve how they are regarded. Increasingly, major companies are choosing to invest in CCS technology, demonstrating commitment to CO₂ reduction as part of their long-term risk management strategies.

CCS is likely to play an increasingly large role in companies’ ESG commitments.

In order to meet the net-zero emissions ambition, a diverse set of clean energy technologies is required. CCS’ crucial role in delivering emissions reductions has been underscored by the IPCC, the UK Committee on Climate Change, the IEA just to name a few. With the need to scale up to more than 2,000 facilities by 2040 we also have no time to lose. While the flow of funding towards new low-carbon technologies is increasing, it is not happening at the pace that is needed. As with renewables when they were in early stages of deployment, targeted public sector signals of support for the industry would help accelerate the market for CCS.
3.3 GLOBAL CO₂ STORAGE OVERVIEW

Global estimates show there are vast storage resources to meet the highest requirements for CCS to achieve climate change targets.

![Global Storage Resource Estimates](image)

**TIME TO FOCUS ON GIGATONNE CO₂ STORAGE**

To meet climate targets, the IPCC climate pathways model up to 1,200 Gt of CO₂ cumulatively stored by 2100\(^2\). There is high confidence that vast CO₂ storage resources are available globally to meet these scenarios. The IEA forecasts that 2.3 Gt of CO₂\(^2\) must be stored each year, by 2060. It means a CCS deployment rate of more than double to that of the growth of the oil industry during the last century\(^3\).

To achieve multi-gigatonne annual CO₂ storage rates, the world will need to characterise, appraise and develop thousands of individual storage sites. The IEA Greenhouse Gas R&D Programme (IEAGHG\(^4\)) estimates that approximately 30-60 storage sites need developing each year until 2050. Adding negative emissions storage, from 2050 and 2100, that number could double. The good news is that the history of oil and gas shows what can be achieved when there is a business case. According to the IEAGHG:

- 350 gas and oil fields were developed annually in the peak development period (2000-2010)
- since 1940, commercial gas resources were discovered at a rate equal to the required rate of development for CO₂ storage resources
- the number of rigs (used to drill for exploration and CO₂ injection wells) required to develop CO₂ storage sites is only 20 per cent of the total rig count.

Recognising the importance of CCS to meeting emission reduction targets, several countries have implemented initiatives to identify CO₂ storage sites:

- The US is identifying a series of sites which could store 50Mt or more of CO₂
- Norway and UK both completing significant public databases of CO₂ storage formations across the North Sea
- EU nations producing a storage formation-scale atlas
- Australia undertaking site-scale evaluations with seismic and core analysis around the country
- Japan completing an offshore drilling campaign to test CO₂ storage formations.
MONITORING IS CRITICAL TO ENSURE THAT COMMUNITY EXPECTATIONS ARE MET

Monitoring, measurement and verification (MMV) play a vital role in ensuring CO₂ storage meets operational, regulatory and community expectations. CO₂ storage uses MMV technologies and the experience of the oil, gas, and groundwater industries. The key focus of a CO₂ MMV programme is tracking the CO₂, pressure field, and the surrounding geology around the storage formation. Groundwater and surface monitoring are also common place in most MMV programmes.

Seismic imaging is the most commonly used method to ensure the plume is behaving as expected. With repeated 3D seismic, under certain conditions, a plume can be tracked as it moves through the storage formation. Passive seismic and downhole seismic are increasingly being employed to minimise the footprint and cost of deployment and long-term monitoring.

Pressure monitoring is one of the oldest downhole-based technologies. By measuring the pressure of the formation, an operator can confirm the containment of CO₂. Any shift in pressure may indicate a change in conditions. Also, monitoring the pressure of surrounding formations can rapidly detect if the CO₂ does move out of the storage formation. Along with pressure monitoring, a suite of geophysical testing, such as tracers, and geophysical logging tools are also employed. Collectively, these downhole tools can provide high-resolution conformance and verification of the CO₂.

The primary driver for surface monitoring is to meet community expectations. In an appropriate well-characterised site, the likelihood of CO₂ reaching the surface is diminishingly small. Hence, surface monitoring primarily focuses around boreholes (legacy or operational) that provide the only direct path from the storage formation to the surface. Geochemical analysis measures soil or surface water for elevated CO₂ levels. In the offshore, geochemical sampling is also employed, along with bubble detection systems and sonar to identify potential leaks. The automation of sampling is decreasing costs and the physical footprint of monitoring.

During the first wave of CO₂ storage operations, risk-assessment based MMV programmes demonstrated to regulators and stakeholders that CO₂ storage is predictable and permanent. In many cases, the number of tools operators use to prove conformance and verify the CO₂ is gradually being reduced. The cost of MMV is reducing as the community understand the low risk of CO₂ storage, and tools and techniques become more sophisticated.

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3.1 Global Status of CCS
3.3 Global CO₂ Storage Overview

3.0 Global Status of CCS

Over 260 million tonnes of anthropogenic CO₂ has been injected and permanently stored to date—most through enhanced oil recovery (EOR). Increasing oil production this way is a standard, mature and routine global operation. It is important to emphasise that CO₂ → EOR is not suitable for every oil field. But where CO₂ is suitable to enhance oil recovery the process is as follows:

1. CO₂ is injected into the oil field’s rock formations where it behaves as a solvent, swelling the oil and mobilising oil previously trapped in the rock’s pore spaces.
2. A proportion of the CO₂ moves through the formation as a CO₂ plume, known as free phase CO₂. As more CO₂ is exposed to the rock, it dissolves into surrounding brine. Some becomes immovably trapped in the pore spaces—residual trapping. These same trapping mechanisms occur during dedicated storage.
In the two years since the U.S. Congress passed a milestone CCUS incentive, 45Q tax credit, a number of projects have initiated development. In the same period, an interesting theme has emerged: states and utilities have set themselves goals to have carbon-free electricity.

States such as California and New York have committed to achieving zero-carbon power systems. Utilities that provide over 40 per cent of US electricity have committed to reducing their CO₂ emissions between 80 to 100 per cent.

CCUS will not only play an important role in fulfilling above commitments, but also help meeting even bolder goals that will include decarbonizing industrial emissions and leveraging zero-carbon fuels. This creates implications on federal and state governments to enact additional CCUS enabling policies.

First, we need cheaper capture technologies that are faster to build. This requires federal funding to support transformational technology research and development.

Second, we need financial incentives to commercially deploy CCUS. This will lead to multiple technology vendors providing standardized components, reducing custom engineering needs and banks that are familiar enough with CCUS to readily finance projects.

Third, we need to expand the network of CO₂ pipelines and storage sites such that CO₂ capture projects can easily connect to it, much like a commercial laundromat would connect to the existing water and sewage lines.

Finally, broader climate policies such as procurement mandates, emission caps and energy standards must embrace CCUS, promoting wide-scale deployment.

If we meet these four categories of CCUS policy goals, then we will at least have a chance to meet our mid-century climate goals. That is what is at stake.
3.4 Legal and Regulatory Overview

Policy makers and project proponents agree that practical, well-defined legislation and a strong global regulatory framework are necessary for CCS to reach its potential. The US state of California’s CCS Protocol which accompanies the Low Carbon Fuel Standard (see section 4.2 Regional overview: America), has allowed the development of a regulatory model that addresses the requirements of operators, and wider public concerns. Generally though, progress continues to be slow. Several jurisdictions are yet to even examine their legal frameworks and in some existing regimes, movement is limited, continuing the uncertainty for those seeking to invest in CCS.

In recent months, the most notable legal and regulatory development is a proposal to address a key barrier found in international marine agreements. Article 6 of the London Protocol governs the Parties’ export of wastes for dumping in the marine environment. An unintended consequence of this Protocol is that it effectively bans transboundary transportation of CO2 for geological storage. The signatories to the London Protocol passed an amendment to resolve this issue in 2009, however two thirds of the Protocol’s contracting parties must ratify the amendment for it to come into force. So far only Norway, United Kingdom, Netherlands, Finland, Estonia and Iran have done so. At the London Convention meeting in early October, the Parties of the London Protocol agreed to allow provisional application of the 2009 amendment of Article 6 to the London Protocol allowing for cross-border transport and export of CO2 for geological storage in sub-sea geological formations.

Adopting the resolution will not set a precedent and will only be binding upon those Parties that choose to be provisionally bound by the amendment. If the Parties accept the interim solution, there will be legal certainty about cross-border CO2 transport for CCS climate emissions mitigation. Our analysis of potential ‘hot-spots’ for activity within the scope of Article 6, are set out in Figure 13 (opposite). The hot-spots represent locations where transboundary storage is likely because a nation has limited storage potential, but neighbouring jurisdictions can store CO2 on their behalf. As seen from Figure 13, there are multiple opportunities for transboundary shipment of CO2 worldwide, especially in Europe and Asia.

The current status of some forms of CO2 transportation under European legislation, also remains uncertain. Amendments have been made to the European Union Emissions Trading Scheme (EU ETS) Directive to include CO2 capture, transport by pipelines and the geological storage of CO2 within its scope of activities. Covered installations are no longer required to surrender emissions allowances for the CO2 they have successfully captured for subsequent transportation by pipelines and geological storage, and they can benefit from the EU ETS carbon price. The scope of the Directive, however, applies narrowly to CO2 transport by pipelines and those installations that plan to transport CO2 by other means, e.g. by ships or trucks, would still need to pay for these emissions. The legislation as it currently stands, therefore poses a regulatory barrier to those projects that wish to transport CO2 through different means (e.g. trains and barges).

Figure 13: Legal Hot Spots: Locations where transboundary storage is likely

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Is it Time to Adopt a New Approach to Liability?

Liability is often raised by policymakers, regulators and project proponents as a potential barrier to widespread CCS deployment. It continues to be an issue globally, despite the adoption of various detailed CCS-specific frameworks in recent years. Our Thought Leadership Report examined the issue through policy and legislative analysis and interviews with policymakers, regulators, lawyers, project proponents and insurance sector representatives. The report — Lessons and Perceptions: Adopting a Commercial Approach to CCS Liability — concluded that effort must be made to dispel the widely-held view that liability could be a ‘showstopper’ for the technology, and to give the public and private sectors greater confidence that it can be managed. Adopting a more commercial approach will ultimately see a shift in focus from high-level concerns, towards identifying successful practices and models, as well as eliminating the remaining obstacles to more widespread deployment.

The following actions are central to a more commercial approach:

- Clearly determine what is meant by the term liability. While there are potentially a wide range of liabilities applicable to CCS operations throughout the project lifecycle, their impact differs greatly when considered individually.
- Examine options for addressing greenhouse emissions/climate liabilities, which present unique challenges to both operators and regulators alike.
- Consider the role of both government and the private sector in allocating and managing risks and consequently liability. Experience to-date reveals that there are options which may reduce parties’ exposure and support project deployment.
- Renewed engagement with the insurance sector. Timely and more regular engagement will be necessary if insurers are to develop new products to assist operators manage their potential liabilities.
- Ensure a close and robust dialogue, between project proponents and regulators. Experience demonstrates that engagement has assisted both parties in determining the practical requirements of legislation, or where there is ambiguity in its application.

To download our report Lessons and Perceptions: Adopting a Commercial Approach to CCS Liability please visit globalccsinstitute.com
4.0 REGIONAL OVERVIEWS
The role of CCS in climate change mitigation is highlighted in the IPCC SR15 report and in a range of recent analyses and studies. Several ongoing international processes are poised to have an impact on CCS’s wider, global deployment. These include the pledges and cooperative approaches under the Paris Agreement, Green Climate Fund (GCF) and carbon offsetting scheme for international aviation.

Under the Paris Agreement, Nationally Determined Contributions (NDCs) act as the main opportunity for countries to highlight their commitment to using CCS technology. So far, ten countries (Bahrain, China, Egypt, Iran, Iraq, Malawi, Norway, Saudi Arabia, South Africa and United Arab Emirates) have done so. CCS has near-term relevance for an estimated 50-60 countries who are well-positioned to use it over the coming decades. Some of these countries have previously shown strong interest in CCS, but did not include it in their Nationally Determined Contribution (NDC). The Institute expects that many will over the next cycles.

Signatories to the Paris Agreement are invited to submit their long-term low-greenhouse-gas emission development strategies to the United Nations Framework Convention on Climate Change (UNFCCC) by 2020. Ten of the 13 strategies submitted as of August 2019, include CCS. As more are submitted, the Institute will form a clearer picture of where CCS fits in the long-term emissions reduction planning of countries and regions.

Article 6 of the Paris Agreement offers countries another option to support wide scale deployment of CCS. Negotiations are underway around co-operation between nations to fulfil their pledges through joint action, which would also bring down compliance costs. With growing interest in CCS technologies, this approach may help to establish CCS projects in developing countries.

The UNFCCC is increasingly seeing technology transfer as one of the key mechanisms to achieve climate change mitigation and adaptation. Their Technology Executive Committee’s work plan for the next four years includes the “role of emerging technologies”. The Technology Mechanism will look at improving access in developing nations, and IEA has concluded that the largest deployment of CCS must occur in non-IEA countries. The GCF listed CCS as one of the technologies to transform energy and industry, in their strategic programming for the first replenishment. The replenishment process has had an excellent start, with announcements from over a dozen of countries to double their pledges and the total amount of the first replenishment already exceeding the previous pledging conference in 2014.

The GCF is an excellent potential source of funding for new CCS projects in developing countries because it allows project developers to access significant levels of funding at more affordable rates than would otherwise be available.

The International Civil Aviation Organization is currently developing a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The scheme aims to stabilise CO2 emissions of international aviation at 2020 levels. The rulebook is still being written, but airlines will need to offset their emissions by purchasing international credits from other sectors, or taking actions themselves.

The CCS community will closely follow this industry because airlines may purchase carbon credits from CCS projects or even develop emission reduction projects of their own.

### CARBON, CAPTURE, UTILISATION AND STORAGE (CCUS) RECOGNISED BY G20 LEADERS IN JAPAN

June was a good month in politics for CCUS technologies. The first success was being included in Karuizawa’s G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth communique, for the first time ever.

And then, the opportunities offered by CCUS technologies for the energy transition were recognised within the official G20 Osaka Leaders’ Declaration, following Japan’s hosting of the event. The admittance of CCUS, as well as hydrogen, into the Declaration marked another first.

The Declaration acknowledged, “the role of all energy sources and technologies in the energy mix and different possible national paths to achieve cleaner energy systems.” It stated that all G20 Leaders:...recognise opportunities offered by further development of innovative, clean and efficient technologies for energy transitions, including hydrogen as well as, depending on national circumstances, the Carbon Capture, Utilisation and Storage (CCUS), taking note of work on ‘Carbon Recycling’ and ‘Emissions to Value’. Signatories reaffirmed that they will, “communicate, update or maintain our NDCs, taking into account that further global efforts are needed (by 2020)” and emphasized, “the importance of providing financial resources to assist developing countries”.

The Institute looks forward to more progress before the 2020 G20 summit in Riyadh.

The IEA has consistently highlighted that CCUS is critical to meeting our global climate goals. Last year, global energy demand accelerated at its fastest pace this decade, with fossil fuels meeting around 70 per cent of this growth and contributing to a historic high for energy-related CO2 emissions. In fact, for more than 30 years, the share of fossil fuels in the world’s energy mix has remained virtually unchanged at around 81 per cent. CCUS is a necessary bridge between the reality of today’s energy system and the increasingly urgent need to reduce emissions. Not only can it avoid locking in emissions from existing power and industrial facilities, it also provides a critical foundation for carbon removal or negative emissions. But so far, the vast potential of CCUS remains largely unrealised.

### STORING A NECESSARY BRIDGE BETWEEN THE REALITY OF TODAY’S ENERGY SYSTEM AND THE INCREASINGLY URGENT NEED TO REDUCE EMISSIONS.

When I was spending holidays in the Swiss Alps during the ’60s, all the residents of the village were taking their garbage in their car to dump them in a valley where a little river was flowing. The waste would burn day and night and produced smoke with a horrible smell. But all this was completely legal. Why don’t we do it anymore? Because today it’s prohibited.

The result of stopping people from throwing rubbish into the valley and paying for its disposal was the creation of new industries - waste collection, energy recovery, recycling - that created jobs and profit. Why is it then that companies can still dump as much carbon into the atmosphere as they wish? Why should it be treated differently?

Today, we must correct this market failure. Putting a price on carbon will provide incentives to capture, reduce or eliminate harmful emissions. Doing so is not adding a new tax, but merely correcting an old injustice, and will open the door to the market of the century – protection of the environment.

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**FIGURE 14 PARIS AGREEMENT AMBITION MECHANISM**

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**TABLE 11 ADVANCE DATES FOR THE PARIS AGREEMENT COMMITMENTS**
The Americas are home to 13 of the world’s large-scale operating CCS facilities. The region has advanced thanks to supportive policy frameworks, abundant geological storage, diverse stakeholder support, and a wealth of private-sector expertise. Notably, the United States of America (US) Congress continues to reinvigorate push toward championing technology. In this environment which offers industry the confidence to invest, CCS projects continue to roll-out, cementing the region’s global position.

This was a year of multiple milestones:

- The Shell Quest facility in Canada celebrated capturing its four millionth tonne of CO₂.
- Eight new facilities in the Americas were added to the Institute’s database of large-scale CCS facilities, creating a total of ten projects in various stages of development. There are many projects at conceptualization stage, several will progress in coming years.
- Occidental Petroleum and Carbon Engineering announced the first large-scale direct air capture with carbon storage (DMCCS) project. With a capacity of 1 Mtpa, the project results from the policy confidence offered by the Federal 45Q tax credit and a CCS-Amendment to California’s LCFS.
- The Oil and Gas Climate Initiative (OGCI) indicated that it will invest in (what will be) the US’s largest dedicated geologic storage project – an ammonia production facility by Wabash Valley Resources, storing 1.5 Mtpa of CO₂.

### UNITED STATES OF AMERICA

Section 45Q of the Internal Revenue Code establishes tax credits for storage of CO₂. Congress extended and increased these in 2018 so they provide for USD 35 per tonne of CO₂ permanently stored via enhanced oil recovery and USD 50 per tonne of CO₂ stored geologically – if projects commence construction by 2024. Although seen as the world’s most progressive CCS-specific incentive, Section 45Q is yet to be fully implemented, creating uncertainty about which projects are eligible. The Internal Revenue Service, tasked with implementation, sought comments from stakeholders in mid-2019 and a draft guidance is expected by early 2020. The latter stakeholders are seeking an extension to the construction deadline.

The IPCC’s Report on Global Warming of 1.5°C inspired a shift in lawmakers’ discourse, progressing the climate conversation to one of debating solutions. Building on the passage of 45Q, several bills were introduced in 2019. The Utilising Significant Emissions with Innovative Technologies (USE IT) Act, a top priority for many CCS advocates, would provide further clarity on CO₂ infrastructure permitting procedures and requirements. Other bills deal with matters such as addressing emissions from natural gas power plants and industrial facilities, and how to optimize incentive structures and R&D programs.

California’s LCFS is a credit-based trading mechanism aiming for a 20 per cent reduction in the intensity of the state’s transportation fuels by 2030. Since January 2019, it has included a CCS protocol. Recently trading at an average of USD 194 per tonne of CO₂, the credit applies to CCS projects that lower the emissions intensity of fuels in the California market. DMCCS projects anywhere in the world are included, in recognition of the fact that CO₂ concentration in the atmosphere is a transnational problem.

State-level action in the US has been plentiful. After California – historically regarded as the gold standard of climate policy – passed its zero-carbon electricity mandate and carbon-neutrality by 2050 goal, other states followed. Six states have now 100 per cent carbon-free energy goals in their electricity markets. States like Montana, Louisiana, Texas, and North Dakota provide tax incentives for CCS deployment, while others like Wyoming, are aiming to substantially progress CCS.

The US, which leads the world in progressing CCS and looks set to continue in first place, has excellent opportunities for demonstrating the versatility of CCS applications in both power and in industry:

1. The power sector accounts for 28 per cent of the US’s greenhouse gas emissions. About half of total new generation capacity between now and 2050 will likely come from unabated fossil-fired power. These assets, expected to operate over a lifetime of more than 30 years are risking to lock-in CO₂ emissions through mid-century. Gas fleets are also young and growing, and retiring nuclear, which provides more than 60 per cent of carbon free power, will probably be replaced only partially by zero-carbon resources. An analysis of 45Q has shown that it could spur retrofits of coal and natural gas power plants; capturing 49 MtCO₂ by 2030. CCS solutions in the United States will provide a blueprint for many other countries to follow. In 2019, the Institute added four power plant retrofits to our Institute database (CO2RE.CO).
2. The US industrial sector accounts for another 22 per cent of total emissions. Some of these emissions stem from sources such as ethanol or ammonia production, or natural gas processing, where CO₂ capture is at the low end of the cost scale, ideal targets for CCS.

### REGIONAL DEVELOPMENTS


### KEY US POLICY

Section 45Q of the Internal Revenue Code establishes tax credits for storage of CO₂. Several CCS supportive bills were introduced in 2019 including the INFT Act. California’s LCS is a credit-based trading mechanism applies to CCS projects that lower the emissions intensity of fuels in the California market.

### ADVANCING CCS

In this region, CCS-deployment is supported by strong policy frameworks, abundant geological storage, diverse stakeholder support and a wealth of private-sector experience.

### NEW WAVE OF FACILITIES

In 2019 the Global CCS Institute added 8 new large-scale facilities in the Americas to our database.

### CO₂ CAPTURE

These facilities combined capture 29.9 Million tonnes per annum (Mtpa) of CO₂.
Interest in accelerating CCS deployment remains strong across the Americas:

- Canada's Government joined the ranks of BHP, Occidental Petroleum and Chevron through investing $25 million in the Canadian Direct Air Capture (DAC) company Carbon Engineering through Canada's Strategic Innovation Fund.
- In Brazil, the Petrobras Santos Basin Pre-Salt Oil Field CCS has been separating CO₂ onsite as part of natural gas processing since 2013 and is now storing 3 Mtpa. The captured CO₂ is injected directly into the Lula, Sapinhoá and Lapa oil fields for enhanced oil recovery. Stakeholders are keen to speed up CCS use; mainly in coal and natural gas power plants, but also in the ethanol sector.
- With funding from the World Bank CCS Trust Fund, two CCS pilot projects are progressing in Mexico. The CCS Capture Pilot Project (CCPP) and the CO₂ EOR and Storage Pilot Project (CESP). Significant planning and scoping have been completed and the projects are expected to proceed in early 2020.

The potential convergence of industry, transport and energy policies under the umbrella of comprehensive climate action, is driving government initiatives and policy innovation that supports CCS. The focus must now be on these policies, and their ability to deliver steel in the ground.

CCUS is the global answer to climate change. It is the only solution that can truly mitigate climate change and provide reliable energy production through a realistic mix of renewables and natural resources—all while preserving and creating jobs, economic growth and social stability.

While CCUS is finally gaining limited awareness, we’re not yet scratching the surface on the volume of mainstream attention needed to scale up support from legislators who can ensure government policies and incentives are in place to expedite industry CCUS investments.

The urgency to bring viable CCUS projects to life is now, and the International Brotherhood of Boilermakers is fully committed to raising our collective voices to advocate for CCUS as the bridge to a cleaner energy future and the right solution to save our way of life and our planet.
In November 2018, the European Commission (EC) published its vision for a climate neutral Europe by 2050 in “A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.” CCS is one of seven building blocks in this strategy, and in the various scenarios put forward, its contribution ranges from 52 to 606 MtCO₂ per year in 2050—a strong case for CCS in supporting Europe’s path to a climate neutral economy. The strategy’s scenarios rely on CCS mainly for industrial de-carbonisation, delivering negative emissions through BECCS and producing low-carbon hydrogen.

Aside from climate and energy policy, there is a major development in the field of sustainable finance in Europe, which can help direct financial flows towards wider deployment of CCS. The EU taxonomy for sustainable investments, currently being negotiated between the Council of the EU, the European Parliament and the EC, will create a common language for all actors in the financial system, steering public and private capital toward sustainable investments. The technical report on EU Taxonomy sets technical screening criteria for activities that can make an important contribution to climate change mitigation. CCS is highlighted under several activities. If the technical criteria and the outcome of political negotiations follow the current path, the taxonomy can become a strong driver for institutional investment in CCS across the EU and, potentially globally.

Norway, United Kingdom and the Netherlands are already strong supporters of CCS, and the number of countries showing interest in these technologies continues to increase. Most notably, Germany is talking about CCS again with Chancellor Angela Merkel confirming in May 2019 that Germany must reach climate neutrality by mid-century. Three CCS facilities currently in development – Net-Zero Emissions from Capturing and Utilising a CO₂ Stream (NECSOS) in Norway, the Advanced CCS Research Facility in the Netherlands and the industrial CCS demonstration project in the UK (in Scotland and Yorkshire) – are at advanced stages of development. The remaining 60 per cent, linked to innovation, are based on CCS contributions to industrial decarbonisation, delivering negative emissions through BECCS and producing low-carbon hydrogen.

The Innovation Fund is the largest fund available for financing CCS in Europe. It finances innovative low-carbon technologies and processes in energy intensive industries, CCUS, renewable energy and energy storage projects. Ten billion euros are hoped to be made available, based on a €22 carbon price when 450 million EU ETS allowances are auctioned in 2020-30. Innovation Fund grants can be combined with other funding sources; for example, with EU instruments like Horizon Europe or Connecting Europe Facility, with national programmes, or with private capital.

Aside from climate and energy policy, there is a major development in the field of sustainable finance in Europe, which can help direct financial flows towards wider deployment of CCS. The EU taxonomy for sustainable investments, currently being negotiated between the Council of the EU, the European Parliament and the EC, will create a common language for all actors in the financial system, steering public and private capital toward sustainable investments. The technical report on EU Taxonomy sets technical screening criteria for activities that can make an important contribution to climate change mitigation. CCS is highlighted under several activities. If the technical criteria and the outcome of political negotiations follow the current path, the taxonomy can become a strong driver for institutional investment in CCS across the EU and, potentially globally.

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Beyond the two operating projects in Norway, the full-scale project in Norway and PORTHOS in the Netherlands are the most advanced European CCS projects under development. Both are expected to reach final investment decision in 2020-21 and could operate as soon as 2023-24. They offer open access transport and storage infrastructure and, as the last year, had discussions with regional emitters with an interest to use this shared infrastructure. Third party CO2 storage is an increasingly attractive business opportunity. Other European projects are in varying stages of development:

- In October, the ATHOS project – a consortium of Gasunie, Energie Beheer Nederland B.V. (EBN), Port of Amsterdam and Tata Steel – finalised their feasibility study in the North Sea canal area. They showed that a CCUS network is technically feasible and that it could help companies in the area reduce their emissions by 7.5 MTCO2 per year by 2030.
- The UK’s Teesside cluster gained the support of OGCI Climate Investments. A commercial scale gas-powered power plant equipped with CCS, it is expected to be the anchor project for the cluster, now named Net Zero Teesside.
- Pilot testing of C-Capture’s amine free capture technology was performed at the UK’s largest 3.8GW power station, Drax.

By capturing emissions from biomass combustion, this important project could deliver negative emissions at scale. Drax, Equinor and National Grid Ventures announced in May 2019 that they plan to develop a net zero CCS and hydrogen cluster in the surrounding Humber region, called Zero Carbon Humber.

Existing and developing European projects rely on offshore CO2 storage, avoiding public opposition to onshore storage. Several plan to re-use oil and gas infrastructure; improving project economics and utilising well understood geological features. The Ervia Cork CCS project in Ireland, for example, is expected to use the depleted Kinsale area offshore gas fields and infrastructure to store CO2 produced by two combined cycle gas turbines and nearby industry.

Hydrogen is playing an increasingly important role in the strategies of European countries who want to decarbonise key sectors like transport, industrial processes and district heat. Several CCS projects incorporate the production of hydrogen through steam methane reforming of natural gas, while capturing and storing the associated CO2. The Acorn CCS and hydrogen project at the St Fergus Gas terminal in Scotland is a notable initiative. Around 35 per cent of all UK natural gas comes onshore at St Fergus, providing an ideal location for blending hydrogen into the national grid and decarbonising natural gas.

The way CCS projects are planned in Europe has changed considerably during the last decade. The focus used to be on building full chain solutions where one source of emissions would build their own transportation pipeline to their storage site. Now, most projects are planned as hubs and clusters.

Capturing CO2 from clusters of industrial installations, instead of single sources, and using shared infrastructure for the subsequent CO2 transportation and storage network, will drive down unit costs across the CCS value chain. Keeping a network open for third party CO2 deliveries, increases economies of scale. Using a mix of transportation including pipelines and ships – but also trains and trucks – offers flexibility and accessibility to a wider range of CO2 sources around the industrial clusters. Several major industrial regions are planning CCS cluster development:

- Netherlands – Port of Rotterdam and Port of Amsterdam
- Belgium – Port of Antwerp
- UK – Humber and Teesside.

The Ruhr industrial cluster in Germany is expected to benefit from the CCS projects developed across the border in the Netherlands.

A dedicated multi-partner ALIGN-CCUS project aims to contribute to the transformation of six European industrial regions into economically robust, low-carbon centres by 2025. The project will create blueprints for developing low-emission industry clusters through CCUS and assess commercial models for CO2 cluster developments, including public-private partnerships.

The regulatory barrier of non-pipeline CO2 transport under EU ETS will need to be addressed in the next couple of years for Europe to fully benefit from the economies of scale offered by hubs and clusters (see section 3.4 for more information).

In September, the Norwegian Government hosted a high-level CCS conference in Oslo, together with the European Commission. During the event Equinor, on behalf of the Northern Lights partners, signed agreements to develop value chains in CCUS with:

- Air Liquide
- ArcelorMittal
- Ervia
- Fortum Oyj
- HeidelbergCement AG
- Preem
- Stockholm Exergi

The parties will cooperate on CO2 handling and transport to Northern Lights.

**HUBS AND CLUSTERS IN EUROPE**

**NORWAY CONTINUES TO ADVANCE ITS EUROPEAN CCS AMBITION**

A leading country in CCS development globally, Norway has geologically stored more than 20Mt of CO2 in the past 20 years. The Sleipner and Snøhvit projects were the first in the world to store CO2 offshore and are the only operational large scale CCS facilities in Europe.

A planned full scale CCS project will involve capturing CO2 at multiple industrial facilities, then transporting it for storage. Operated by Equinor with partners Shell and Total, the facility will uniquely use ship-based transport, thus enabling the storage of CO2 from major sources across North West Europe. The transport and storage element of the project – Northern Lights – will be open access infrastructure.

The initial Norwegian sources of CO2 - Fortum’s Oslo Varme waste-to-energy plant and Heidelberg Cement’s Norcem cement plant in Brevik – have performed FEED studies and site testing. A drilling campaign will soon start to study the suitability and capacity of the Johannsen formation in the Norwegian Continental Shelf for storing CO2.

Based on its experience with CCS, the Norwegian Government hopes to use this project as the catalyst for wider deployment of CCS in Europe. The use of sea-based transport means industry across Western Europe can also store and transport their CO2 through Northern Lights.

**FIGURE 19: POTENTIAL SOURCES OF CO2 FOR NORTHERN LIGHTS**

*Note:* Diagram shows potential sources of CO2 for Northern Lights. The parties will cooperate on CO2 handling and transport to Northern Lights.
At the 2018 UN Climate Change Conference (COP 24) in Poland, the UK Government shared its world-leading ambition to develop the first ‘net-zero carbon’ cluster by 2040. Backed by up to £370m, the announcement is already stimulating UK clusters. Hydrogen production is a common feature:

- Net Zero Teesside plans to develop an industrial cluster in the North East of England. It is one of five global CCUS hubs supported by OGCI’s CCUS KickStarter initiative. Each year the cluster plans to capture up to 6 million tonnes of CO2 from a gas-fired power plant and other industrial sources and could be fully operational by 2030.
- Zero Carbon Humber is a partnership to build a zero-carbon industrial cluster in England’s Humber region. Pilot testing for a BECCS project is underway at the UK’s largest power station, Drax, and there are plans for a hydrogen and CCS network in the surrounding area. Figure 21 shows the anticipated timeline for the project, culminating in over 10 Mtpa of CO2 abated51.
- The Acorn project plans a major hydrogen and CCS hub at St Fergus in Scotland. Here, 35 per cent of all UK natural gas comes onshore, making it the ideal place to blend hydrogen directly into the grid. The project took a major step forward in late 2018 when it was awarded the first carbon dioxide appraisal and storage licence by the Oil and Gas Authority, the independent regulator and licensing authority for offshore carbon dioxide storage in the UK.

In parallel to these major projects, innovative UK companies continue to develop novel CCUS technologies. Two examples of success are:

- C-Capture has developed a non-amine based capture technology, now being tested at Drax.
- Carbon Clean Solutions was selected for the world’s largest cement-based carbon capture project in India, using its patented CDRMax technology.

With Scotland hosting COP 26, the year ahead is bound to be another where CCUS takes purposeful strides forward in the UK.
**OVERVIEW**

Capturing 1.6 Mtpa of CO₂

1.6 Mtpa

5-30 Gt

**HYDROGEN OPPORTUNITY**

Low carbon hydrogen production, from natural gas with CCS, in the Middle East is estimated to cost only USD1.50/kg.

**CENTRAL ASIA**

Rapidly increasing energy demands being driven by growing population, rising living standards and urbanisation that is largely met by fossil fuels.

**POLICY AND CCS MOVEMENT**

Saudi Arabia and the United Arab Emirates (UAE) are members of Mission Innovation and the Clean Energy Ministerial.

Both countries have committed to doubling public investment in clean energy research and development and are participating in the Clean Energy Ministerial’s CCUS initiative.

**MIDDLE EAST**

Natural gas demand is expected to continue to rise in the Middle East, driven by the growing industrial sector, power generation demands and the growing petrochemicals industry. Countries in the region are increasingly aware of the need to decarbonise their oil and gas production and the importance of diversifying toward new energy economies. CCS can play an important role in the Middle East to support energy demand and the transition to cleaner energy sources. With vast and accessible underground CO₂ storage potential, abundant cost-competitive gas resources and hydrogen production facilities with excess capacity, the Middle East has potential to become a hub for CCS development and deployment.

The region could also use its location and natural gas and pore space resources to develop a clean hydrogen export industry. Clean hydrogen production, from natural gas with CCS, in the Middle East is estimated to cost USD1.50/kg.

Saudi Arabia and the United Arab Emirates (UAE) lead this region’s efforts, each hosting one large-scale CCS facility that is supported and operated by State Owned Enterprises. Abu Dhabi captures CO₂ from steel production and Uthmaniyah, Saudi Arabia from natural gas processing, both supply CO₂ for enhanced oil recovery.

Abu Dhabi National Oil Company (ADNOC) recently announced that it would be scaling up efforts to reduce its emissions 10 percent, by 2023. CCS will play a role. In the next decade, ADNOC aims to scale-up CCS deployment six-fold, capturing five million tonnes of CO₂ by 2030.

In October 2019, Qatar, now the second’s largest exporter of LNG, announced that it aims to capture and store five million tonnes of CO₂ by 2030. Emissions will be captured from either the Habshan-Bab complex, or the Shah plant.

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The Asia Pacific region is the source of just over half of the world’s total CO2 emissions. This heavy emissions profile is driven by large, rapidly growing and developing economies which rely on fossil fuels for power generation. Many countries, particularly those across South East Asia, have young fleets of fossil fuel power stations with decades of economic life, and are planning more. There are 352 GW of coal fired power plants under construction or in planning for the near-future.

In 2017, the Asia Pacific was responsible for 72 per cent of the world’s coal consumption. China made up nearly half of this; followed by South East Asia, Korea and Japan. Increasing coal power generation in Indonesia, Bangladesh, Philippines and Vietnam is driving future fast-demand.

Switching from coal to gas for industrial and residential uses, particularly in China, has increased demand for liquefied natural gas (LNG). It is predicted to account for almost 60 per cent of total global energy consumption by 2024. Led by China and India, Asia Pacific economies also produce more than half of the world’s most emissions-intensive products, such as steel and cement.

These challenges combined with inertia around developing low-carbon policy mechanisms and lack of legal and regulatory regimes to incentivise CCS investment could create the assumption that there is little room for CCS technologies. But, with air pollution on the rise, CCS deployment cannot happen soon enough. Encouragingly, in the past year, the Asia Pacific has continued to strengthen its position as one of the most active CCS regions in the world, with 12 large-scale facilities either operating or in various stages of development.

China leads CCS activity across the Asia Pacific with one large-scale facility in operation, two in construction and five in early development. China also contributes almost one third of the world’s CO2 emissions and has the most urgent requirement to reduce them.

Following the 2018 restructure, the Chinese Government focused on a more coordinated approach to general environmental management, combining emissions reductions with air pollutant controls, to stimulate new industries and jobs. Their new National CCS Professional Committee will provide government with direct support and advice on relevant industrial standards and policy-making, striving to enhance international cooperation on CCS.

In May 2019, the latest Roadmap for CCUS in China was published. It clarified the strategic position of CCUS and proposed mid to long-term targets and priorities for achieving low carbon transition through affordable, feasible and reliable CCUS technologies. The Institute expects that these significant policy commitments to cut emissions and advance low carbon technologies will advance the deployment of CCS.

India’s 2019 announcement of the world’s 19th large-scale CCS project, a first for Australia. When fully operational, Geelong will be the world’s largest dedicated geological storage facility.

In 2018, India’s emissions rose by 4.8 per cent. IEA estimates that, by 2040, India will account for 20 per cent of global industrial CO2 emissions being captured and stored.

In June, the Japanese Government submitted its Long-Term Strategy under the Paris Agreement, to the UNFCCC. The strategy identifies CCS alongside other emission-reduction technologies, to deliver deep emission reductions to power generation and industrial processes including the production of clean hydrogen, and states the Government of Japan’s intention to collaborate with the private sector and other governments on a range of initiatives designed to reduce barriers to CCS deployment.

Indian company Dalmia Cement has committed to becoming carbon negative by 2040 and sees CCU as one of the solutions it needs to get there. In September 2019, the company announced plans for a large scale 0.5 Mtpa carbon capture facility in Tamil Nadu, in partnership with Carbon Clean Solutions who will provide the plant’s technology. Dalmia is looking for multiple utilisation streams from the carbon capture plant.

The Hydrogen Energy Supply Chain project (HESC) is a significant example of Japanese government collaboration with the private sector and other governments to commercialise CCS. This project being developed by Kawasaki Heavy Industries (KHI), Electric Power Development Co. (J-Power), Jswatan Corporation, Marubeni Corporation, Sumitomo Corporation and ACL, with the support of the Governments of Japan, Australia and the State of Victoria, will demonstrate the production of hydrogen from coal in the Latrobe Valley of Victoria and the transport of hydrogen by ship from Australia to Japan. Construction of the gasifier commenced in November 2019 and first hydrogen production is expected by 2021. If this pilot is successful, an investment decision to construct a commercial scale clean hydrogen production facility with CCS in the Latrobe Valley, to supply Japan could be made in the mid 2020s.

The Asia Pacific region is responsible for almost 50% of the world’s coal consumption. In 2017, Asia Pacific region was responsible for 72 per cent of the world’s coal consumption. In 2018, India’s emissions rose by 4.8 per cent, alongside a sharp increase in energy demand and a five per cent growth in demand for coal. It has the world’s third largest coal fleet, with an average plant age of 14 years and growing infrastructure demands which draw on energy intensive materials like steel and cement, of which India is the world’s second largest global producer. Importantly, in its clean technology scenario, the IEA estimates that, by 2060, India will account for 20 per cent of global industrial CO2 emissions capture and storage. CCS can underpin a meaningful energy transition for this region, offering rapid decarbonisation for clean and sustainable economic development.

The Japanese Ministry of Economy, Trade and Industry (METI) and Ministry of the Environment (MOE) continue to drive Japan’s comprehensive CCS program. This program is multi-dimensional, addressing the full CCS value chain from the development, and demonstration of capture technologies, investigating effective regulatory models, exploring policy options for commercial deployment, identifying and characterizing storage reservoirs and CO2 transport options, and understanding CCS business models.

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Other 2019 updates for CCS in Japan:

- With ongoing support from Japan’s Ministry of Economy, Trade and Industry, CCS Co. Ltd’s Tomakomai CCS facility, remains Asia’s first full-cycle CCS hydrogen plant. In 2019, it reached a capture milestone of 300,000 tonnes of CO2, and continued intensive monitoring of storages.
- Construction continued at Toshiba Corporation’s 49MW Mikawa power plant in the Fukukou Prefecture for biomass (and coal) with carbon capture. Completion is expected in early 2020.
- A new CO2 capture plant was established in August 2019, continuing progress at the Osaki CoolGen facility in the Hiroshima Prefecture. The IPower and Chugoku Electric Power Company’s 146 MW oxygen-blown integrated gasification combined cycle (IGCC) facility will separate and capture CO2 from the end of 2019. Solid oxide fuel cells will make up stage-three.
- Toshiba’s carbon capture and utilisation system at the Saga City waste incineration plant, started operating, using captured CO2 for algae culture.

AUSTRALIA

If Australia is to play a significant role in the global market, it will need to engage in global energy markets and align regulatory frameworks with other countries. Australia has a significant potential for the deployment of CCS technologies, particularly in the energy and industrial sectors.

The government of Japan approved “the Long-Term Strategy under Paris Agreement” at a cabinet meeting in June 2019. The Strategy holds that Japan needs to reduce its CO2 emissions by 80 per cent by 2050, declaring “a de-carbonized society” as its ultimate goal, and aiming to achieve it as early as possible in the second half of this century. Under this long-term vision, CCS is regarded as a technology contributing to substantial GHG emission reductions in the future.

So far, Japan has been working on a large-scale demonstration test at Tomakomai, Hokkaido, research and development on CO2 separation and safety management technologies, and a study of facilities for sites, aiming for the practical application of the CCS technology around 2020. Especially, the demonstration project at Tomakomai, which draws global attention, achieved the accumulative CO2 injection amount of 240,000 ton as of the end of September 2019, having made successful progress in coordination with local stakeholders.

Meanwhile, in order to realize the future societal implementation of CCS in Japan, further reduction of CCS costs and availability of transportation from distant CO2 sources to suitable storage sites are the key to addressing issues such as the high cost of CO2 capture. The government of Japan is promoting the development of CCS technologies, and is collaborating with the local and global community, to realize the commercialization of CCS.

In summary, the government of Japan is promoting the international cooperation and the development of CCS technologies, and is collaborating with the local and global community, to realize the commercialization of CCS.

The government of Japan has in 2019 approved the “the Long-Term Strategy under Paris Agreement” to aim for the decarbonization of society by 2050. In 2020, the government is aiming to achieve a 78 to 85 per cent reduction in CO2 emissions from 1990 levels. The government is also working on the development of CCS technologies, and is collaborating with the local and global community, to realize the commercialization of CCS.

Since 2012, Japan CCS has been steadily accumulating various results and achievements in the Tomakomai CCS Demonstration Project, and has been seeking for multilateral and bilateral cooperation for the promotion of CCS technologies. The Tomakomai CCS Demonstration Project is playing an important role in the development of CCS technologies, and is collaborating with the local and global community, to realize the commercialization of CCS.

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6.0 APPENDICES

7.0 REFERENCES
In 2018, demand for natural gas grew at its fastest pace since 2010, accounting for almost half of added global energy demand. It is expected to grow at a rate of 1.6 per cent per year through to 2024, largely because it is seen as a fix to worsening air quality in non-OECD countries, can replace retiring coal in Europe, and is undercutting coal in the US. The IEA’s Sustainable Development Scenario sees gas demand stabilising slightly below this forecast somewhere between the mid-2020s and 2040. While gas power generation produces half the carbon dioxide emissions of coal, at around 350 kg CO2 per megawatt hour (MWh) for the most efficient combined cycle gas plant, it is not considered a low emissions technology. Natural gas production and processing also produce significant CO2 emissions. Eliminating almost all greenhouse gas emissions along the natural gas value chain is necessary if we are to meet the target of net-zero emissions by mid-century. More than 700 Mtpa of indirect CO2 emissions—almost equal to the emissions of Germany in 2016—could be eliminated from oil and gas operations through the application of CCS. Applying CCS at gas processing facilities costs around USD20-25 per tonne CO2. It is not only one of the lowest cost CCS-applications, but is already capturing 25 Mtpa at ten of 19 operating large-scale CCS facilities. Even so, roughly 150 Mtpa of effectively pure CO2 is still being vented from facilities around the globe. CCS can play a role in laying out a sustainable path for natural gas to become one of the preferred fuels of the future.

The liquefied natural gas trade is forecast to grow by a quarter to 830 Mtpa by 2050, equivalent to the annual emissions of the UK in 2016. In 2018 alone, the EU and 18 national governments made notable hydrogen announcements and by mid-2019 there were 50 incentives in place globally to support its use. Hydrogen is expected to play a major role in decarbonising industrial processes, transport, domestic heating, and possibly electricity generation (see Figure 23 below).

## 5.1 Natural Gas

### Decarbonising Power, Industry and Kick-Starting the Energy Transition

A new gas-based power generation technology is being developed by NetPower which offers the promise of electricity generation with carbon capture for the same cost as conventional natural gas combined cycle generation. The technology utilises the Allam Cycle. In a conventional natural gas combined cycle generator, the combustion gases from methane burnt in an air driven gas turbine which in turn drives a generator to produce electricity. The exhaust gases from the turbine then pass through a heat exchanger to heat water creating steam which drives a second turbine, also connected to the generator, producing additional power. The flue gases consist mostly of nitrogen (from air), carbon dioxide and water. Capturing the carbon dioxide from the flue gases of a conventional gas powered generator requires the installation and operation of a capture plant to separate the carbon dioxide, which makes up only about 10 per cent, from the other gases, mostly nitrogen. This adds cost and reduces the amount of electricity produced. In a conventional gas powered generator, the power required to run the carbon dioxide capture plant may reduce the overall efficiency of the generator by 50 to 15 percentage points.

The Allam Cycle burns gas in an atmosphere of oxygen and carbon dioxide producing only carbon dioxide and water in the combustion gases, which then drive a turbine and a generator. The hot exhaust gases pass through a heat exchanger, condensing the water (which is removed), and the remaining pure carbon dioxide is re-compressed and an amount equal to that continuously added from the combustion of methane is bled off at high pressure ready for transport and geological storage. The remaining carbon dioxide is re-heated in the heat exchanger and recycled into the combustion unit and turbine. Even though significant power is required by the air separation unit necessary to produce the oxygen for the combustor, the efficiency advantages of the Allam cycle over conventional combined cycle gas generators produce equivalent overall efficiencies (almost 60 per cent). However, the Allam cycle enjoys a very significant advantage over conventional gas power systems with respect to the capture of carbon dioxide as it requires no additional equipment or power to separate carbon dioxide from its flue gases, ready for geological storage. There is no parasitic load, no loss of efficiency and no reduction in electricity produced. Demand for clean hydrogen is expected to grow strongly. A briefing paper prepared for the Australian Commonwealth and State Governments on the development of a National Hydrogen Strategy envisages demand exceeding 530 Mtpa by 2050, up from 70 Mtpa today.

Currently, 98 per cent of global hydrogen production is from unabated fossil fuels, around three-quarters stemming from natural gas. CO2 emissions from its production are approximately 830 Mtpa, equivalent to the annual emissions of the UK in 2016. To meet climate targets, hydrogen must be produced via zero or very low emission pathways. The European Commission and several countries have already directly identified CCS as a key consideration for achieving this. Australia, New Zealand, Japan, China, the US and the Netherlands have also indicated their importance in their hydrogen policies (see Appendix 6.3 for details).

### The Allam Cycle Opportunity

The Gorgon CCS project was established due to a condition of the project’s approval—the gas field contains 14 per cent of Australia’s natural gas. CO2 emissions from its production are approximately 830 Mtpa, equivalent to the annual emissions of the UK in 2016. Australia, New Zealand, Japan, China, the US and the Netherlands have also indicated their importance in their hydrogen policies (see Appendix 6.3 for details).

### The Focus on Hydrogen

Hydrogen regained the spotlight in 2019 as a multipurpose, clean fuel for a net-zero future, producing no greenhouse gas emissions when used. The breadth of regions, countries and cities with strategies and supportive policies for using and producing hydrogen, demonstrates global recognition of the fuel’s potential to decarbonise economies.

In 2018 alone, the EU and 18 national governments made notable hydrogen announcements and by mid-2019 there were 50 incentives in place globally to support its use. Hydrogen is expected to play a major role in decarbonising industrial processes, transport, domestic heating, and possibly electricity generation (see Figure 23 below).

### 5.2 Hydrogen

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### Inputs & Fuels

In 2018 alone, the EU and 18 national governments made notable hydrogen announcements and by mid-2019 there were 50 incentives in place globally to support its use. Hydrogen is expected to play a major role in decarbonising industrial processes, transport, domestic heating, and possibly electricity generation.
HYDROGEN PRODUCTION WITH CCS

The three main technologies used to produce low-carbon hydrogen are:

- gas reforming (mostly from steam methane reforming) with CCS;
- coal gasification with CCS; and
- electrolysis powered by renewables.

Each technology offers its own benefits and will play a role in the global energy transition. The advantages of low-carbon hydrogen production through gas reforming and coal gasification with CCS, centre around the maturity of the technologies, scale and commercial viability.

MATURITY

Low-carbon hydrogen has been produced through gas reforming and coal gasification with CCS, for almost two decades. For example, the Great Plains Synfuels Plant in North Dakota, US, commenced operation in 2000 and produces approximately 1,300 tonnes of hydrogen (in the form of hydrogen rich syngas) per day, from brown coal. Hydrogen produced from coal or gas with CCS is the lowest cost clean hydrogen by a significant margin and requires less than one tenth of the electricity needed by electrolysis. Where renewable electricity is available, low-carbon hydrogen made with CCS will be competitive with hydrogen produced through electrolysis. CCS hydrogen costs two thirds less.

SCALES

For hydrogen to make a meaningful contribution to global greenhouse gas emissions reductions, it will need to be produced in very large quantities to displace a significant proportion of current fossil fuel demand. Scaling up low-carbon hydrogen production with CCS is proven, operating at commercial scale and available for deployment right now. Hydrogen produced using coal or methane with CCS costs USD1.70-2.40 per kilogram compared to USD7.45 for hydrogen produced via electrolysis. CCS hydrogen costs two thirds less.

Price will be a key decider of whether hydrogen plays a significant role in emissions reduction. Low-carbon hydrogen produced using gas reforming and gasification technologies with CCS is proven, operating at commercial scale and available for deployment right now. Hydrogen produced using coal or methane with CCS costs USD1.70-2.40 per kilogram compared to USD7.45 for hydrogen produced via electrolysis. CCS hydrogen costs two thirds less.

Action is required now to ensure hydrogen can play its role in the global energy transition, at the scale required to meet emissions reductions targets. Scaling up low-carbon hydrogen production with CCS will require capital grants or incentivising policies from governments, a value on carbon and market mechanisms to create demand.
5.3 CCS IN POWER SECTOR

Most planned and active CCS projects are in industrial sectors where high concentration CO₂ is readily available and can be captured at relatively low cost. However, to enable sustainable economic growth and elevate living standards while achieving Paris Agreement targets, deep emissions reductions are needed across all sectors, especially the power sector. There are only two large-scale CCS facilities currently operating there\(^\text{10}^\). Rapid deployment of renewable energy has reduced the amount of dispatchable power required from fossil fuel sources, but the nature of intermittent energy systems mostly not designed for intermittent generation\(^\text{10}^\). High levels of intermittent energy may even substantially increase overall system costs\(^\text{4}^\). Coal and gas fuelled power stations equipped with CCS delivers dispatchable low emissions electricity demanded by advanced economies, and requires no additional measures to ensure grid resilience and reliability of supply. As the penetration of intermittent renewable generation in a grid increases, additional investment in transmission augmentation, energy storage, demand side management and artificial inertia is also required. The lowest cost low emissions electricity grid will require dispatchable low emissions generators alongside intermittent renewable generation capacity.

According to the IEA, existing and under construction energy facilities account for around 95 per cent of the emissions "budget" under its SDS\(^\text{10}^\). Coal-fired power stations make up one third of total energy-related emissions globally. To enable continued operation in a low-carbon world, asset owners need to conduct economic and technology feasibility assessments on retrofitting options. In developing countries, especially in Asia where coal fired power plants have an average age of eleven years\(^\text{10}^\) and decades of economic life, retrofitting CCS will be required to reduce emissions.

Under the IEA’s SDS, it is expected that 350 MtCO₂ will be captured and stored from the power sector in 2030\(^\text{10}^\). Since large-scale CCS projects in power have long lead times – in the range of 6-10 years – the power sector must take substantive steps now, to meet those targets in 20-20 years.

5.4 BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

Bioenergy with Carbon Capture and Storage (BECCS) is a promising class of technologies. The production of sustainable biomass is considered to be renewable energy, so its integration or fermentation with CCS technology, achieves negative emissions. Bioenergy is used to fuel vehicles (as bioethanol) and to provide electricity through biomass combustion, displacing fossil fuels as a source of thermal energy. It is considered one of the few scalable carbon dioxide removal options. BECCS is a feature of IPCC scenarios consistent with limiting global warming to 1.5 degrees\(^\text{9}^\). Despite its potential, there are some serious hurdles ahead of wide scale BECCS deployment:

- Productivity and resource requirements for different types of land and biomass vary significantly. Growing forest based residues uses 1.7-1.8 hectares for every tonne of CO₂ removed annually while purpose-grown energy crops need approximately 0.1-0.4 hectares\(^\text{12}^\).
- Producing crops specifically for BECCS can involve land clearing, which may reduce or even reverse its carbon removal potential\(^\text{2}^\).
- Wide scale deployment of BECCS could compete or overlap with land available for forest creation or food production, leading to significant changes in ecosystems\(^\text{14}^\).
- Producing biomass at the scale required demands large amounts of water and fertiliser.

Apart from the IEA, several prominent organisations (Royal Society, Stanford University, Imperial College London and others) remain committed to BECCS, viewing it as an essential technology in the fight against climate change. Many private sector companies also see BECCS as a way to decarbonise and shelter themselves from carbon prices, or as a means to meet regulation requirements. In July 2013, UK based Drax power station converted the first of its six boilers to fire using biomass. Their decision was made in response to the UK Government’s SDS2025 deadline for phasing out coal in the power sector. Drax initiated a CCS pilot project in 2018 which now captures 3 tonnes of CO₂ per day. If successful, the pilot will pave the way towards negative emissions in the UK.

The other main application of BECCS uses fermentation to produce bioethanol. Bioethanol production produces a relatively pure stream of CO₂ gas which presents an opportunity for low cost capture and makes BECCS facilities a relatively low cost development. This could be especially relevant in developing countries, which are responsible for approximately 35 per cent of global ethanol production\(^\text{14}^\).

The Institute regards the deployment of BECCS as a proven and important complement to CCS, so long as it uses sustainably sourced biomass. It cannot, however, be relied upon as the only form of CCS. It is one option in a suite of solutions.
5.5 DIRECT AIR CAPTURE (DAC)

Direct Air Capture (DAC) is a modular technology that can capture CO₂ directly from the atmosphere using chemicals that bind or stick to it. CO₂ can then be stored or repurposed into CO₂ re-use applications, such as manufacture of construction aggregates, plastics and synthetic fuels.

There are two promising groups of DAC technologies:

• Large infrastructural DAC using water solutions containing plastics and synthetic fuels.
• A modular technology based on amine materials bonded to a porous solid support. The process operates at 85°-120°C requiring far less heat energy. There is potential for future reductions through mass production.

Compared to other forms of negative emissions (carbon dioxide removal i.e. trees), DAC facilities require little land. There are however, concerns about its requirement for large amounts of water and energy to extract low concentration CO₂ from the atmosphere. Recent models estimate that if DAC was the only CO₂ removal method used to avoid a rise of 1.5°C in global average temperature by 2050, its energy requirements would represent approximately half of current global energy consumption[115].

• Climeworks, a Swiss company utilising modular DAC technology, estimates its capture costs to be between USD500-700 per tonne CO₂ stored. It relies on support from individuals and companies, willing to purchase emissions reduction certificates for a higher price than they could get on a market like the EU ETS. Climeworks aims to bring the cost of storage down to approximately USD100 per tonne CO₂, so that it can access a larger market and upscale the technology.

• Development of the world’s largest DAC plant was recently announced by Oxy Low Carbon Ventures and Carbon Engineering Ltd in the US. They are working on the engineering and design to look at carbon as a viable feedstock for the chemicals, polymers, and other materials that go into their products and supply chain executives are engaging with utilisation companies. Given their marketing prowess, these companies have the potential to drive a consumer pivot to low carbon goods, supporting the whole CCU space.

5.6 CO₂ UTILISATION

In the next several decades, the geological storage of CO₂ will do the vast amount of work to meet climate goals. However, carbon utilisation has an important role to play. To illustrate, Mac Dowell et al estimate that up to 700 million tonnes per annum of CO₂ could be utilized by 2050[117]. Estimates by the IPCC of the amount of CO₂ that must be stored using CCS by the middle of the century to limit global warming to 1.5 degrees are around 5000 to 10,000 million tonnes per year[118].

Carbon utilisation will expand investment in the testing and refining of capture technologies and can be used to permanently sequester CO₂ at locations where transportation pipelines are impractical or not economically feasible.

CCUS is the process of capturing CO₂ to be recycled for further use. Carbon utilisation’s effectiveness as a positive weapon in the fight against climate change depends on how it is used. It can be ‘substituted’ for natural CO₂ in EOR, or be used as an input to the production of something of value. Interest and investment in converting CO₂ to a different form or substance is recently booming.

In general terms, CO₂ utilisation delivers emissions abatement where:

• The CO₂ utilised would have otherwise been emitted to the atmosphere and it remains permanently stored (EOR) or bound in the product (e.g. concrete).
• The CO₂ utilised would have otherwise been emitted to the atmosphere and the product displaces a product of fossil fuel origin (e.g. production of synthetic liquid fuels displacing diesel).
• The CO₂ utilised would have otherwise been emitted to the atmosphere and is recycled for further use (e.g. greenhouse horticulture).

CO₂ ‘SUBSTITUTE’

Dutch waste recycling and waste-to-energy firm AVR is beginning construction of a large-scale CO₂ capture system in its Duiven plant. The pure CO₂ stream, once an industry by-product, will be transported by Air Liquide to greenhouse horticulture areas in the Netherlands. A similar project is occurring in Saga, Japan. Both projects will see enhanced plant growth through the addition of extra CO₂ while avoiding the use of natural CO₂ or natural gas for cultivation.

CO₂ ‘REPURPOSED’

Other companies have developed technologies to permanently store CO₂ in building materials and chemical products:

• CarbonCure, Blue Planet, and Solida Technologies have various sized concrete and aggregates projects underway worldwide, many in North America.
• BluePlanet bubbles waste gases from California’s largest power plant at Moss Landing through seawater, collecting CO₂. Around 90 per cent is removed and then combined with minerals in the water to create limestone.
• LanzaTech creates chemical products and fuels using emissions from industrial facilities, and has several projects around the globe.
• Cemvita Factory uses CO₂ as the feedstock for sustainable production of intermediate chemicals and polymers.

There are some significant but (relatively) easily faced challenges to overcome before scaling up CO₂ utilisation technologies:

• policy and regulatory environments need to be more supportive;
• lifecycle greenhouse gas emissions must be appropriately accounted for, including energy inputs, to determine net carbon reductions; and
• costs need to keep coming down.

However, it must be stressed that whilst the emissions abatement that can be delivered through CO₂ utilisation is valuable, their contribution to the emissions abatement challenge is limited.

FIGURE 25 UTILISATION AND STORAGE PATHWAYS

Part of the appeal of carbon utilisation is that it allows businesses to think about single-use carbon as a thing of the past, and is a way to engage in the circular economy.

Commitment to a circular economy can be a key strategy for companies wanting to reduce their environmental footprint. It’s attractive to many large consumer brands who intrinsically understand that their future marketing strategy needs to cover how they are addressing climate change. Consumer brands are beginning to look at carbon as a viable feedstock for their intermediate chemicals, polymers, and other materials that go into their products and supply chain executives are engaging with utilisation companies. Given their marketing prowess, these companies have the potential to drive a consumer pivot to low carbon goods, supporting the whole CCU space.
5.0 CCS development: Technology and Applications
5.7 CCS Innovation

5.7 CCS INNOVATION

Carbon dioxide capture has been an essential part of industrial processes for 90 years, either through chemical absorption (amines), since 1910108, physical absorption, adsorption or a membrane or cryogenic distillation-based separation process. In natural gas processing and urea fertiliser production, CO2 separation is an inherent part of the production process, so the cost for capture is very low109. In other industries like hydrogen, iron and steel and cement production, and in waste-to-energy, CO2 capture has been proven at commercial scale but not yet widely deployed.

In the power sector, CO2 capture has only recently been applied at two commercial facilities – Boundary Dam since 2015 and Petra Nova since 2017110. The extra costs of capture and the absence of policies to justify investment are primary barriers to large-scale deployment of CCS in power generation. However, good progress has been made to reduce the cost of carbon capture and to optimise performance through project learning. Next-generation capture technologies have also emerged to drive costs down.

PROJECT LEARNING

Providers of goods and services compete to reduce costs and to improve the utility of their products in pursuit of market share. As a market grows, economies of scale and scope and learning-by-doing deliver cost reductions. Innovation happens and can only be protected from competitors for a finite time until knowledge leakage inevitably spreads developments throughout the entire industry. As demand increases, so do capital costs. The net result is the familiar pattern of technology costs reducing over time, in real terms. This is exactly the pattern observed in relation to renewable energy technologies this century, driven by very strong and sustained policy support.

The process of cost reduction is only just beginning in the global CCS industry. Boundary Dam111 and Petra Nova demonstrate how cost innovation is happening, even in the absence of a strong competitive market. Altering design, construction and operations can reduce costs for future carbon capture projects:

- SaskPower reported in 2015 that, based on project learning from the Boundary Dam CCS facility, to Petra Nova Carbon Capture and Storage project, aims to use post-combustion technologies to capture CO2 from a cement plant.
- The LEILAC project recently demonstrated that direct separation (removing CO2 from limestone as it is being heated) could capture more than 95 per cent of CO2 process emissions112.
- Calix is piloting this new, efficient and cost-effective direct separation technology.

Steel and iron production is reliant on coal, as both a feedstock and a fuel, and the industry produces almost as much CO2 every year as cement production113. Unlike cement though, emissions arise at different points in the production process. CO2s must be captured during heating and from the blast furnace when iron is being reduced to make steel. Recent innovations include:

- An alternative to hot metal production and conventional blast furnaces—the smelting Reduction Hirnsen Process has the potential to capture 80 per cent of CO2 emissions from steelmaking when deployed together with CCS114; and
- The launch of the “3D” project (for DMX™ Demonstration) in Dunkirk—a consortium of European stakeholders is piloting the capture of CO2 emissions at ArcelorMittal’s facility.

CHEMICAL INDUSTRY: ETHYLENE AND AMMONIA

The chemical industry, which produces products like plastic, is the industrial sector’s third-largest emitter115. CCS has not been applied at commercial-scale in this sector. Some possibilities are:

- Ethylene, used mostly as a base for plastics, is made from various hydrocarbons that are ‘cracked’ in petrochemical furnaces. Known as steam cracking, most CO2s is generated when fuel heats the furnaces. Capturing CO2s from furnace exhaust gases is already a proven CCS application in the power and iron and steel industries.
- Ammonia, used as a base ingredient for fertilisers and explosives, is a critical input for the agriculture and mining sectors. It is derived from either coal or natural gas, and its production emits a mixture of hydrogen and nitrogen, as well as a large, near-pure, stream of CO2s. Two large-scale CCS facilities already compress, transport and use (for EOR) pure stream CO2s.

Cement

The cement industry contributes 8 per cent of global CO2s emissions116. Heating the kiln for calcination of limestone and then the calcination reaction itself, produces almost all the emissions from clinker production. Around 90 per cent of the CO2s can be captured and stored using CCS, as long as engineering design is optimised. This is happening:

- The LEILAC project recently demonstrated that direct separation (removing CO2 from limestone as it is being heated) could capture more than 95 per cent of CO2 process emissions112.
- Calix is piloting this new, efficient and cost-effective direct separation technology.
- Norway’s Norcem project, which is part of a larger Northern Lights project, aims to use post-combustion technologies to capture CO2s from a cement plant.
CAPTURE TECHNOLOGY INNOVATION

Next-generation capture technologies have unique features – either through material innovation, process innovation and/or equipment innovation – which reduce capital and operating costs and improve capture performance. (See Figure 29 below).

Some of these technologies are already being considered in engineering studies for CCS facilities. They are:

- Ion Engineering’s non-aqueous ICE-21 solvent – selected for a FEED study at Southern Company’s Energy Campus.
- The University of Texas’s piperazine advanced stripper (PZAS) process – selected for a FEED study at the Mustang Station of Golden Spread Electric Cooperative. Next generation technologies are helping to drive down CCS development costs and shorten deployment timelines. Assisted by industry improvements that result from learning-by-doing at facility operation and project management level, these developments are edging CCS closer to widespread deployment.

Carbon dioxide capture rates from low concentration gas streams such a power station flue gas, have historically targeted 90 per cent. This capture rate has almost become the default target however, as described below, there is no technical reason why capture rates in the high nineties cannot be delivered. Notwithstanding what is technically feasible, both of the first retrofits of CCS to coal fired power stations adopted the 90 per cent capture target.

The Boundary Dam CCS retrofit has not achieved an overall capture rate of 90 per cent since it commenced operating due to down time required for maintenance and process improvements. As a first of a kind plant, it is not surprising that operational difficulties were encountered. However these lessons only need to be learned once and the operators of Boundary Dam, SaskPower, make all of their operational data available to share those learnings.

The Petra Nova facility, which is the second retrofit of CCS to a coal fired power station, has avoided similar difficulties. Petra Nova captures 90 per cent of the CO₂ (approximately 1.4 million tonnes per year) from a slip stream of flue gas equivalent to that produced by a 2400MW power station. The capacity of the capture plant was determined by the demand for CO₂. If there was sufficient demand, there is no reason why Petra Nova could not have treated all of the flue gas produced by the power station, at a capture rate of 90 per cent or more.

A 2019 techno-economics analysis by CSIRO and IEAGHG looked at the cost of achieving 99 per cent CO₂ capture in fossil fuel-fired power plants, compared to achieving 90 per cent. Excluding transport and storage, cost went up by three per cent in an ultra-supercritical coal plant and by eight per cent in a natural gas combined cycle.

Figure 30 (below) shows that emissions with CCS can be reduced to:
- 48 grams CO₂eq / kWh (9 grams CO₂eq/kWh direct emissions)
- 89 grams CO₂eq / kWh (4 grams CO₂eq/kWh direct emissions)

Figure 30 also shows that emissions with CCS can be further reduced to:
- 15 grams CO₂eq / kWh (3 grams CO₂eq/kWh direct emissions)
- 21 grams CO₂eq / kWh (5 grams CO₂eq/kWh direct emissions)

This capture rate has almost become the default target however, as described below, there is no technical reason why capture rates in the high nineties cannot be delivered. Notwithstanding what is technically feasible, both of the first retrofits of CCS to coal fired power stations adopted the 90 per cent capture target.

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6.1 LARGE SCALE CCS FACILITIES IN OPERATION

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<td>AIR PRODUCTS STEAM METHANE REFORMER</td>
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<td>GREAT PLAINS SYNFUELS PLANT AND WETBURN-MIDALE</td>
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<td>Synthetic Natural Gas</td>
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<td>19</td>
<td>TERRELL NATURAL GAS PROCESSING PLANT (FORMERLY VAL VERDE NATURAL GAS PLANTS)</td>
<td>Operating</td>
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<td>1972</td>
<td>Natural Gas Processing</td>
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6.2 LARGE SCALE CCS FACILITIES IN CONSTRUCTION, ADVANCED AND EARLY DEVELOPMENT

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<th>TITLE</th>
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<th>COUNTRY</th>
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<td>In Construction</td>
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<td>ALBERTA CARBON TRUNK LINE (ACTL) WITH AGRIUM CO STREAM</td>
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<td>Canada</td>
<td>2010</td>
<td>Fertiliser Production</td>
<td>0.3 - 0.6</td>
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<td>SINOPEC GUI PETROCHEMICAL CCS</td>
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<td>YANCHANG INTEGRATED CAPTURE AND STORAGE DEMONSTRATION</td>
<td>In Construction</td>
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<td>Chemical Production</td>
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<td>PORT OF ROTTERDAM CCUS BACKBONE INITIATIVE (PORTHOS)</td>
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<td>PROJECT TUNDRA</td>
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<td>2015 - 2026</td>
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<td>Advanced development</td>
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<td>HYDROGEN 2 MAGNUM (H2M)</td>
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<td>CHINA RESOURCES POWER PROJECT (INTEGRATED CARBON CAPTURE AND SEQUESTRATION DEMONSTRATION)</td>
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<td>ACCRIN SCALABLE CCS DEVELOPMENT</td>
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### 6.3 HYDROGEN STRATEGIES WITH CCS

#### COUNTRY

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>INCLUSION/DETAIL/IMPORTANCE OF CCS IN HYDROGEN STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUSTRALIA</td>
<td>Consultations by the National Hydrogen Working Group to develop a National Hydrogen Strategy by the end of 2019 are already considering the production of hydrogen using fossil fuels and CCS. In addition, construction at the Hydrogen Energy Supply Chain (HESC) liquefaction and loading facility began in July 2019. The HESC is a project, supported by a consortium of government and industry partners from Australia and Japan, will look at the feasibility of turning brown coal from the Latrobe Valley into hydrogen to be shipped to Japan and using the CarbonNet CCS project to transport and store emissions in the nearby Gippsland basin.</td>
</tr>
<tr>
<td>JAPAN</td>
<td>Host of the 2019 G20, Japan used this important platform to highlight hydrogen. This included hosting the first Hydrogen Energy Ministerial meeting and, in the same month, adopted a carbon-neutrality strategy that includes innovation goals for both carbon capture and hydrogen and launched a Japan H2 Mobility program which aims build up to 80 refueling stations by 2020.</td>
</tr>
<tr>
<td>UNITED STATES</td>
<td>The United States also showed progress in the development of hydrogen production with CCS with provisions added to the 45Q tax credit to incentivize the conversion of CO2 and other products, and included conversion via combination with hydrogen. In addition, the amendment of California’s Low Carbon Fuel Standard to enable CCUS came into effect. This created a way for companies that produce hydrogen via SMR with carbon capture to generate credits, while also incentivizing the roll-out of hydrogen-fueling capacity – thus eliminating one of the barriers to adoption.</td>
</tr>
<tr>
<td>UNITED KINGDOM</td>
<td>In the UK, the majority of hydrogen production is expected to use natural gas with CCS and is being driven by the dedicated policies, reviews and investments in hydrogen as a low emission technology to decarbonise transport and heat sectors, as well as industry. For example, the H2 Leeds Citygate project, after a detailed economic and technical feasibility study conducted in 2018, has proposed to decarbonize the existing natural gas network in the UK city of Leeds by converting it to 10 per cent hydrogen. The project involves a process of hydrogen production using Steam Methane Reforming of natural gas, the associated carbon emissions will be sequestered under the North Sea.</td>
</tr>
<tr>
<td>EUROPE</td>
<td>The Hydrogen Roadmap Europe was published in February 2019 by PHE [E], which consists of members representing the European Commission, Hydrogen Europe and Hydrogen Research Europe. With the aim of supporting research and development in fuel cell and hydrogen energy technologies, the study focuses on pathways for their large-scale deployment until 2050. The production of hydrogen from steam methane reforming processes is highlighted as an avenue for the decarbonization of the transport and industrial sectors. In particular, CCS is recommended for companies as a proven method of producing very low carbon hydrogen on a large scale. The EU’s “Clean Planet for All” decarbonization strategy was published by the European Commission in November 2018. The strategy considers several pathways to reach decarbonisation by 2050. The production of hydrogen from natural gas steam reforming using CCS, for energy storage purposes, energy carrier purposes in the transport, heat and industrial sectors and as a feedstock for industry is considered as a potential decarbonization strategy in these sectors.</td>
</tr>
<tr>
<td>NETHERLANDS</td>
<td>Outlines of a Hydrogen Roadmap was drafted by TKI New Gas (Top Sector Exerg) on behalf of the Ministry of Economic Affairs and Climate Policy. Published in March 2018, the report explores decarbonization pathways using hydrogen in the industrial and transport sectors. The report recommends exploring hydrogen production from natural gas with CCS (blue hydrogen) in order to accelerate large-scale application of hydrogen.</td>
</tr>
</tbody>
</table>


3.0 LEGAL AND REGULATORY OVERVIEW

N/A
ENDNOTES

i. Includes methods of utilisation of CO₂ that permanently prevent CO₂ from entering the atmosphere, such as in cement curing, contribute to emissions abatement.

ii. Data from the Global CCS Institute CO₂RE database as of November 2019 (Global CCS Institute 2019a).

iii. The advanced development stage in a project’s lifecycle means greater detailed investigation through front-end engineering design (FEED) is underway. This may involve steps like choosing the specific technology to use, examining design and overall facility costs, obtaining permits and approvals or assessing key risks to the development. Once this stage is completed, the project may be ready for a final investment decision (FID).

iv. CO₂ Geological Storage Study funded by the US Department of Energy.

v. The Institute is liaising with project developers and reviewing proposed CCS facilities with an eye to including them in our CO₂RE database in early 2020.

vi. Note that the cost of capture from more concentrated CO₂ gas streams, such as biofuel production or hydrogen production from gas or coal, are significantly lower.

vii. GCCSI Analysis based on 8 per cent discount rate, 30 years project life, 2.5 years construction time, capacity factor of 85 per cent. Fuel prices were based on the reported data in the project feasibility and FEED reports. Cost data normalised to 2017 values.

viii. Assuming 50kWh of electricity per kilogram of hydrogen produced.


x. Estimated electricity generated in 2017 from Nuclear was 2637TWh, from all renewables combined was 6351TWh.

xi. See p.71 for more detailed information about coal fired generators with CCS – Boundary Dam and Petra Nova.


xiii. Cost is adjusted to 2018 US$ value calculated using the measure of cost used by (Rubin et al 2015). Cost of flue gas desulfurization process is included in Boundary Dam and Shand.