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CARBON CAPTURE UTILISATION AND STORAGE – STATUS, BARRIERS AND POTENTIAL

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PREFACE

This report has been produced by the IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member organisations.

The IEA Clean Coal Centre was established in 1975 and has contracting parties and sponsors from: Australia, China, the European Commission, Germany, India, Italy, Japan, Poland, Russia, South Africa, Thailand, the UAE, the UK and the USA.

The overall objective of the IEA Clean Coal Centre is to continue to provide our members, the IEA Working Party on Fossil Fuels and other interested parties with independent information and analysis on all coal-related trends compatible with the UN Sustainable Development Goals. We consider all aspects of coal production, transport, processing and utilisation, within the rationale for balancing security of supply, affordability and environmental issues. These include efficiency improvements, lowering greenhouse and non-greenhouse gas emissions, reducing water stress, financial resourcing, market issues, technology development and deployment, ensuring poverty alleviation through universal access to electricity, sustainability, and social licence to operate. Our operating framework is designed to identify and publicise the best practice in every aspect of the coal production and utilisation chain, so helping to significantly reduce any unwanted impacts on health, the environment and climate, to ensure the wellbeing of societies worldwide.

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ABSTRACT

Around 170 GWe of coal-fired power generation with CCUS will be needed by 2050 as part of the transition to a net zero CO_2 emission future. The Asia Pacific, including China, is a key region where this will need to be implemented. This must be achieved as part of a combined approach of limiting global temperature rise, whilst providing access to reliable and affordable energy to support economic development and improved living standards. It forms part of an 'inclusive transition' where OECD countries work with developing nations to move towards a lower emissions future that does not disadvantage an important section of the global population. Good progress has been made in reducing the cost of CCUS through the early commercial-scale demonstration projects and the latest front end engineering design (FEED) studies, with CO_2 capture costs now projected to be in the range of 43-45 US$/t$CO_2$. Further cost reduction can be expected through 'learning by doing' where perhaps 50-70% cut could be achieved from the current cost of around 65 US$/t$CO_2$, as the technology is rolled out commercially. However, to kickstart this roll-out, a strong financial and regulatory regime will need to be put in place which delivers more positive carbon pricing signals, provides investment for carbon transport and storage infrastructure and provides more accessible debt and equity financing on the back of lowering CCUS specific project risk.

ACRONYMS AND ABBREVIATIONS

2DS	2 degrees centigrade scenario, IEA
ASU	air separation unit
B2DS	beyond 2 degrees centigrade scenario
BD3	Boundary Dam Unit 3
BECCS	biomass energy carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy, UK
CAG	CCUS Advisory Group
CCS	carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CfD	contract for difference: UK government's main mechanism for supporting low-carbon electricity
DAC	direct air capture
DOE	Department of Energy, USA
EOR	enhanced oil recovery
EPC	engineering, procurement and construction
ETI	Energy Technologies Institute, UK
ETS	Emissions Trading System, EU
EU	European Union
FCCC	Framework Convention on Climate Change, UN
FEED	front end engineering design
FOA	funding opportunity announcement
FOAK	first of a kind
GCCSI	Global Carbon Capture and Storage Institute
GHG	greenhouse gases
$GtCO_2$	gigatonnes (10^9 tonnes) of carbon dioxide
GW	gigawatts (10^9 watts)
HMG	Her Majesty's Government, UK
IEA	International Energy Agency
IEACCC	IEA Clean Coal Centre
IEAGHG	IEA Greenhouse Gas R&D Programme
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LCCC	Low Carbon Contract Company, UK
LCFS	Low Carbon Fuel Standard
LCOC	levelised cost of CO_2 capture
LCOE	levelised cost of electricity
METI	Ministry of Economy, Trade and Industry, Japan
MHI	Mitsubishi Heavy Industries (supplier of KM CDR Process post-CO_2 capture technology)
MOEJ	Ministry of the Environment, Japan
$MtCO_2$	million tonnes (10^6 tonnes) of carbon dioxide

NDCs	nationally determined contributions (relating to the Paris Agreement)
NG	natural gas
NGCC	natural gas combined cycle
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
Ofgem	Office of Gas and Electricity Markets, UK
OGCI	Oil and Gas Climate Initiative
OM&A	operation, maintenance and administration
R&D	research and development
RAB	Regulated Asset Base (project funding model)
RD&D	research, development, and demonstration
RTS	reference technology scenario
SDGs	Sustainable Development Goals, UN
SDS	Sustainable Development Scenario
SMR	steam methane reforming
SOE	state-owned enterprises
TRL	technology readiness level
UAE	United Arab Emirates
UN	United Nations
UNECE	UN Economic Commission for Europe
WACC	weighted average cost of capital
ZEP	Zero Emissions Platform

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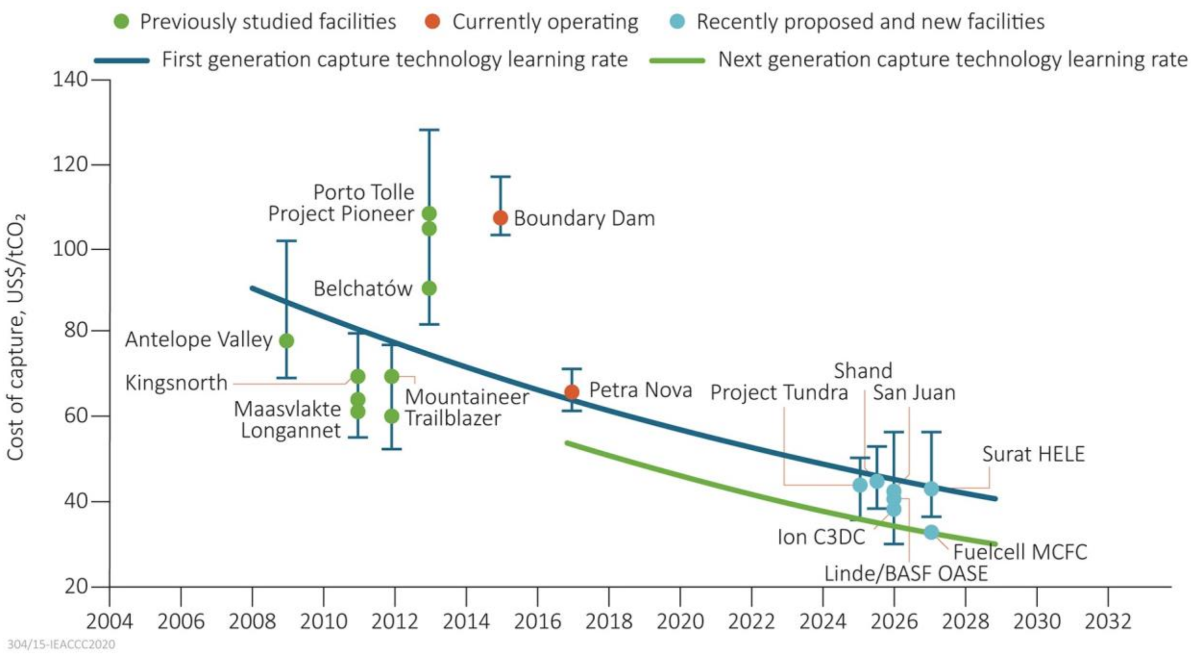
EXECUTIVE SUMMARY

The case for CCUS – Fuel power generation fitted with CCUS is a key part of the transition to a net zero CO_2 emissions future. The International Panel for Climate Change has shown that excluding CCUS from the portfolio of technologies to reduce emissions would double the cost. Around 170 GWe of coal-fired power generation with CCUS will be needed by 2050 to limit global temperature rise to 2°C or below. The Asia Pacific region accounts for more than 50% of global CO_2 emissions and should become a key focus for the roll-out of commercial CCUS.

CCUS technology status – The elements of the CCUS technology chain are in place for commercial deployment, indicating that the barriers to widespread large-scale deployment of CCUS are not technical. Several other next generation technologies that could provide step change cost reductions and increase efficiency are being researched and developed and could in time be on the market.

The cost of CCUS, which is probably the single most important lever for wide-scale roll-out of the technology, has reduced significantly. Recent project studies including the Shand FEED study predict CO_2 capture costs at around 43–45 US$/t$CO_2$ removed cost, within a proposed timescale for commencement of plant operations by 2024-28. Further cost reduction can be expected through 'learning by doing' where perhaps 50–70% cut could be achieved from the current cost of around 65 US$/t$CO_2$, as the technology is rolled out commercially.



Levelised cost of electricity for large-scale coal power generation plant with post-combustion CO_2 capture

Availability of the power plant was an issue in the early CCUS demonstrations, but it has now reached acceptable levels. For example, the Boundary Dam CCUS facility has increased its availability to around 85% over the last two years, in line with the facility's design availability of 85%.

CCUS capture levels will need to increase from the current 85–90% to closer to 100% to allow the power plants to continue to operate in a net zero emission future as any residual CO_2 emissions from CCUS facilities will not be compliant without offset from negative CO_2 emissions elsewhere. Where auxiliary plant are used to provide steam and energy for the CCUS facility, they will also need to include CCUS to achieve very high capture levels overall.

Next steps – Despite the cost reduction that has been achieved to date, CCUS has been deployed in relatively few countries and in general has relied on the revenue stream from enhanced oil recovery (EOR). While this has enabled the first demonstration projects to get off the ground, the policies currently in place are insufficient and further actions need to be taken.

More positive carbon price signals need to be sent to drive the growth in CCUS. Whether the carbon price is effectively valued through carbon emitted, emissions trading schemes or tax credits on the amount of CO_2 stored, the value needs to be around 40–80 US$/t$CO_2$ by 2020, increasing to 50–100 US$/t$CO_2$ by 2030. Currently, less than 5% of global CO_2 emissions have a carbon pricing regime which is consistent with this, a notable initiative being the 45Q tax credit system in the USA which provides 50 US$/t$CO_2$ for geological storage or 35 US$/t$CO_2$ for EOR by 2026.

The 'hub and cluster' approach enables the sharing of transport and storage networks which can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain issues. There is however likely to be an initial investment barrier to the hub and cluster infrastructure where the balance of risk and return is insufficient for initial private sector investment. Here, governments should consider taking this role to kick-start development with the option of privatising the business after it has gained sufficient CO_2 source and sink 'customers'.

The availability of debt financing for CCUS projects needs to increase significantly, with banks having a critical role to play. To qualify for debt financing, CCUS projects will need to provide assurance that key risks are identified with mitigations in place and that 'hard-to-manage' risks are allocated to government in the short term. The cost of debt will need to reduce from the current 14–15% level to below 10% in the medium term, as successive CCUS projects are able to address risk and drive down the cost of debt risk premium.

System/network operators need to recognise the auxiliary services such as reactive power and frequency response provided by coal powered plant and allow for financial compensation for these services. Such services will become increasingly important as the share of non-dispatchable renewable power sources, primarily wind and solar, increase in global power systems. The integration of a CCUS facility must therefore not adversely affect the power plants ability to provide these services.

Compliance with SDGs – CCUS is a key technology contributing in particular to SDG13 – Climate Action, as part of the transition to a net zero CO_2 emissions future. A combined approach of limiting global temperature rise, whilst providing access to reliable and affordable energy to support economic development and improved living standards should be pursued.

1 INTRODUCTION

A number of global assessments (IEA, 2017, 2019a) have reviewed the means to achieve near-net zero CO_2 emissions by the middle of the 21st century. They have identified the key role that carbon capture utilisation and storage (CCUS) should play in various sectors, including fossil fuel power generation, industrial/chemicals markets and as the means of producing hydrogen for power, transport and energy storage.

There are a number of CCUS projects globally, either concluded, currently in operation or proposed, as defined by the Global CCS projects database (GCCSI, 2019b). This includes the large-scale post-process capture demonstrators at SaskPower's Boundary Dam plant in Canada and NRG Energy's Petra Nova plant in the USA. Whilst these projects have to a large extent been successful in demonstrating coal power generation with CCUS, they have not led to a wide-scale commercial roll-out of CCUS.

The aim of this report is therefore to examine the most relevant of the current CCUS demonstration projects. The large-scale coal projects identified above have provided first valuable data on CCUS at scale, which has been used as part of a wider analysis to consider relative performance and carbon capture technologies, together with an examination of the 'lessons learned'. The perceived barriers to the roll-out of CCUS are assessed. Having determined the current barriers, the report then assesses the potential means of overcoming them. Finally, the study makes reference to the most relevant of the 17 United Nations Sustainable Development Goals in relation to the application of CCUS to coal power generation.

The term 'carbon capture, utilisation, and storage' includes technologies such as enhanced oil recovery (EOR) as well as those which convert CO_2 into useful chemical products. The term CCUS will be used throughout the majority of this report, but it should be noted that it is used in reference to geological storage of CO_2, or geological storage in connection with EOR only. A wider assessment of CO_2 utilisation in terms of the potential uses of CO_2 has been covered in a separate report by the IEA Clean Coal Centre (IEACCC), (Zhu, 2018).

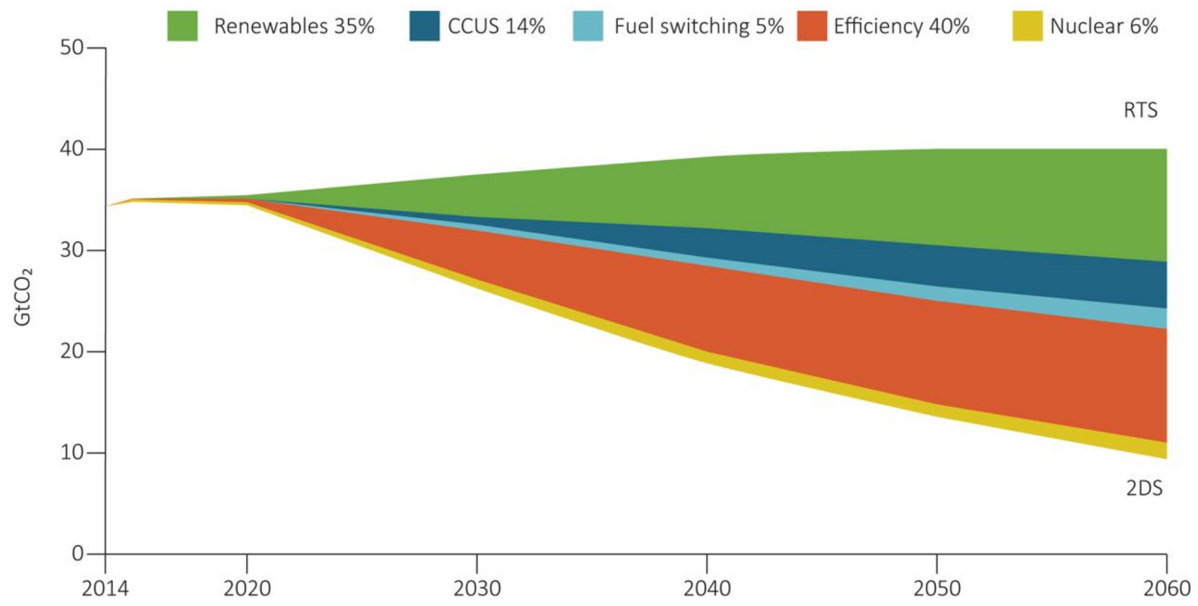
2 THE CASE FOR CCUS

The Paris Agreement on climate change was adopted at the 2015 United Nations Climate Change Conference (COP21). Ratified by 197 governments, the central aim of the agreement (UN, 2015) is to strengthen the global response to the threat of climate change and keep the global temperature increase by 2100 to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. It seeks to balance greenhouse gas (GHG) sources and sinks in the second half of this century, effectively requiring net zero GHG emissions.

In order to achieve these targets, the International Energy Agency (IEA) has analysed the transition in global energy use that would be required. Its Energy Technology Perspectives report (IEA, 2017) sets out pathways to achieve a '2°C temperature rise scenario' (2DS) and a more ambitious 'beyond 2°C temperature rise scenario' (B2DS). These scenarios are compared with the 'reference technology scenario' (RTS). Each scenario is described briefly below with full details provided in the IEA (2017) report:

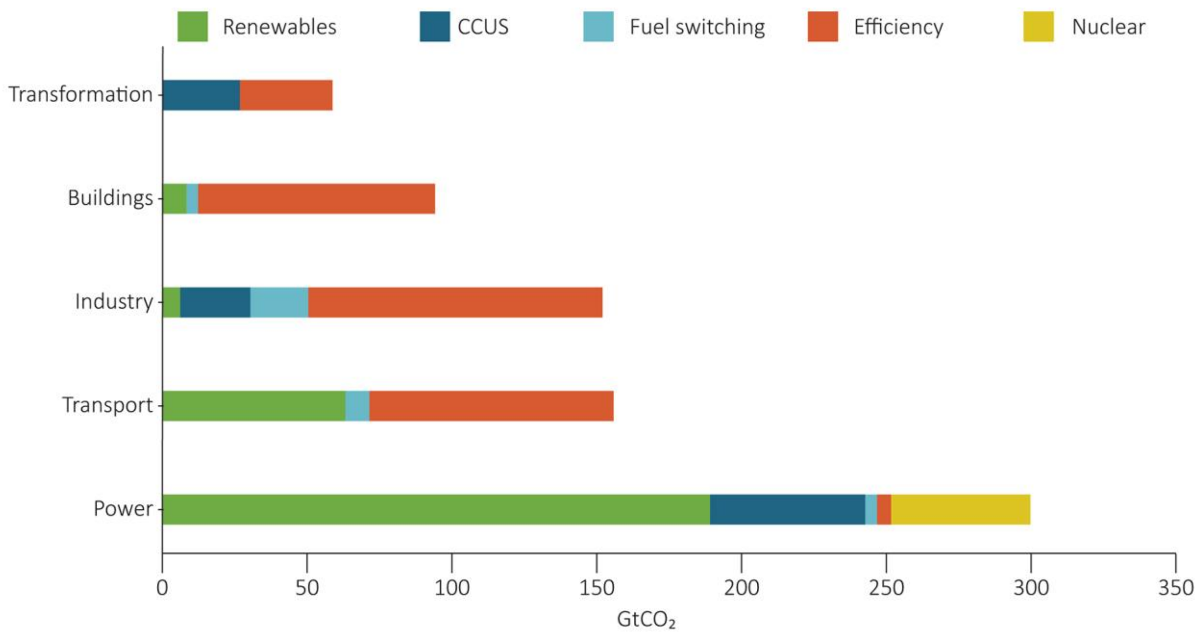
- The 2DS scenario lays out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. Annual energy sector CO_2 emissions are reduced by 70% from the 2014 level by 2060, with cumulative emissions of around 1,170 $GtCO_2$ between 2015 and 2100. To stay within this range, CO_2 emissions from fuel combustion and industrial processes must continue their decline after 2060, and carbon neutrality in the energy system must be reached by 2100. The 2DS is the central climate mitigation scenario, representing an ambitious transformation of the global energy sector.
- The B2DS scenario explores how far deployment of technologies that are already available or in the innovation pipeline could go beyond the 2DS scenario. Technology improvements and deployment are pushed to their limits across the energy system in order to achieve net zero emissions by 2060 and to stay net zero or below thereafter. This 'technology push' approach results in cumulative emissions from the energy sector of around 750 $GtCO_2$ between 2015 and 2100, which is consistent with a 50% chance of limiting average future temperature increases to 1.75°C.
- In comparison, the RTS takes into account the current commitments by countries to limit emissions and improve energy efficiency. The RTS already represents a major shift from the previous 'business as usual' approach. The RTS requires significant changes in policy and technologies in the period to 2060 as well as substantial additional cuts in emissions thereafter. This scenario would result in an average temperature increase of 2.7°C by 2100, at which point temperatures would be unlikely to have stabilised and would continue to rise.

In terms of CO_2 emissions, the 2DS scenario requires cumulative CO_2 emissions to be reduced by 760 $GtCO_2$ by 2060, with 14% of this reduction, a little over 100 $GtCO_2$, coming from CCUS (*see* Figure 1). The power sector is the major contributor to this CCUS-related CO_2 reduction, accounting for more than half, representing over 50 $GtCO_2$ reductions as shown in Figure 2.



304/01-IEACCC2020 Note: CO_2 emissions include both energy-related CO_2 emissions and emissions from industrial processes

Figure 1 Technology mix to achieve CO_2 emissions reduction for the 2DS Scenario (IEA, 2017)



304/02-IEACCC2020 Note: CO_2 emissions include both energy-related CO_2 emissions and emissions from industrial processes

Figure 2 Required CO_2 emissions reduction per sector to achieve the 2DS Scenario (IEA, 2017)

For the B2DS scenario, around an additional 250 $GtCO_2$ emissions reduction is required relative to 2DS, bringing the total required reduction to over 1000 $GtCO_2$, with CCUS providing 32% of this additional emissions reduction (*see* Figure 3).

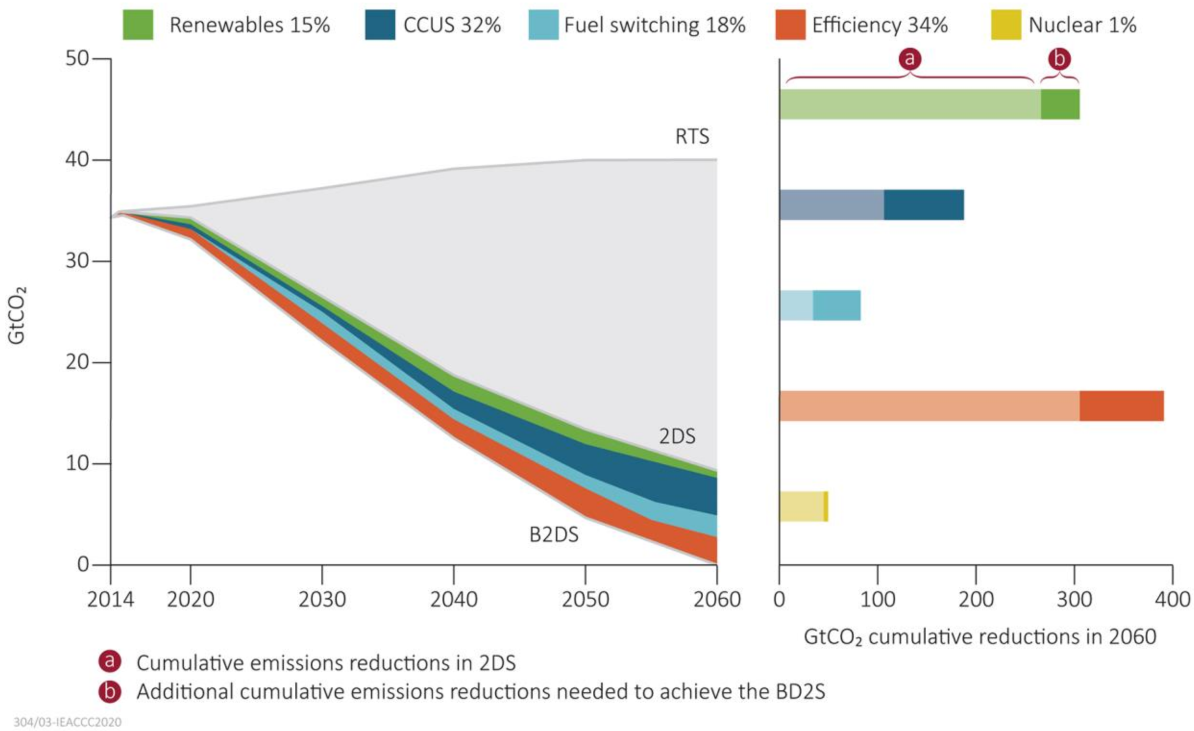


Figure 3 Technology mix to achieve additional CO_2 reduction to move from 2DS to B2DS (IEA, 2017)

The more recent World Energy Outlook study (IEA, 2019a) has looked at the requirements to deliver its Sustainable Development Scenario (SDS), a future where the United Nations energy-related Sustainable Development Goals (SDGs) for emissions, energy access and air quality are met (*see* Chapter 7 for a discussion of the SDGs). This scenario is consistent with a 66% probability of limiting global temperature rise to 1.8°C without relying on large-scale negative emissions (*see* Figure 4). This analysis shows that CCUS provides 9% of the cumulative emissions reduction between 2018 and 2050, accounting for 1500 Mt/y of CO_2 captured and stored.

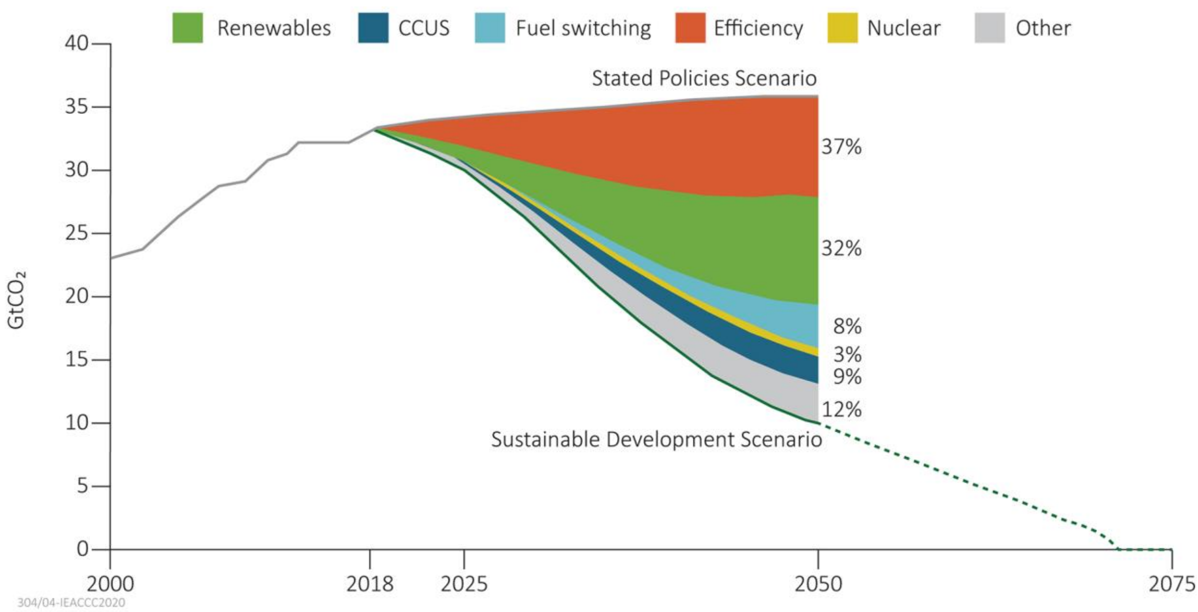


Figure 4 Energy-related CO_2 emissions reduction to achieve the SDS (IEA, 2019a)

This level of CCUS is lower than the earlier IEA Energy Technology Perspectives forecast (IEA, 2017), in part due to the 2017 Energy Technology Perspectives 2DS and the 2019 World Energy Outlook SDS results being from two different modelling exercises with different time periods. At a high level, the SDS relies much more on solar and wind in the power sector and less on CCUS and nuclear than earlier analyses.

In addition, analysis by the Intergovernmental Panel on Climate Change (IPCC, 2019), IEA (IEA, 2017) and national studies such as the Energy Technologies Institute in the UK (ETI, 2018), have shown consistently that CCUS is an essential part of the lowest cost path towards meeting climate targets. The IPCC's Fifth Annual Assessment Report (AR5) showed that excluding CCUS from the portfolio of technologies used to reduce emissions would double the cost, and the ETI study showed that the UK's decarbonisation costs would also double by 2050 without CCUS.

Whilst the above IEA analysis has looked at scenarios that would be necessary to achieve a 2°C or better temperature rise this century, other studies have 'forecast' what the most likely future could be. One such study (DNV GL, 2019) is described as a 'technology heavy' and 'policy light' forecast. It concludes that the transition in energy is happening fast, but not fast enough to hit Paris Agreement targets, projecting around a 2.4°C temperature rise by the end of this century. Their single forecast indicates that the 1.5°C CO_2 budget could already be exceeded by as early as 2028 and the 2°C budget by 2048. It should be noted however that there are uncertainties associated with this estimate (*see* DNV GL, 2019 for details). In terms of CCUS, a significantly lower uptake of the technology is forecast compared with the policy driven scenarios as above. In this forecast, it is only when carbon prices start to approach the CCUS cost level in the 2040s that any significant uptake occurs. By 2050, only 0.8 $GtCO_2$/y representing around 4% of fossil fuel-related emissions, would be captured and stored. There would be large regional variations in this, with 50% of all captured emissions in China, 20% in Europe and 12% in North America. Coal-related CO_2 capture in the power sector accounts for around 80 $MtCO_2$/y (*see* Figure 5).

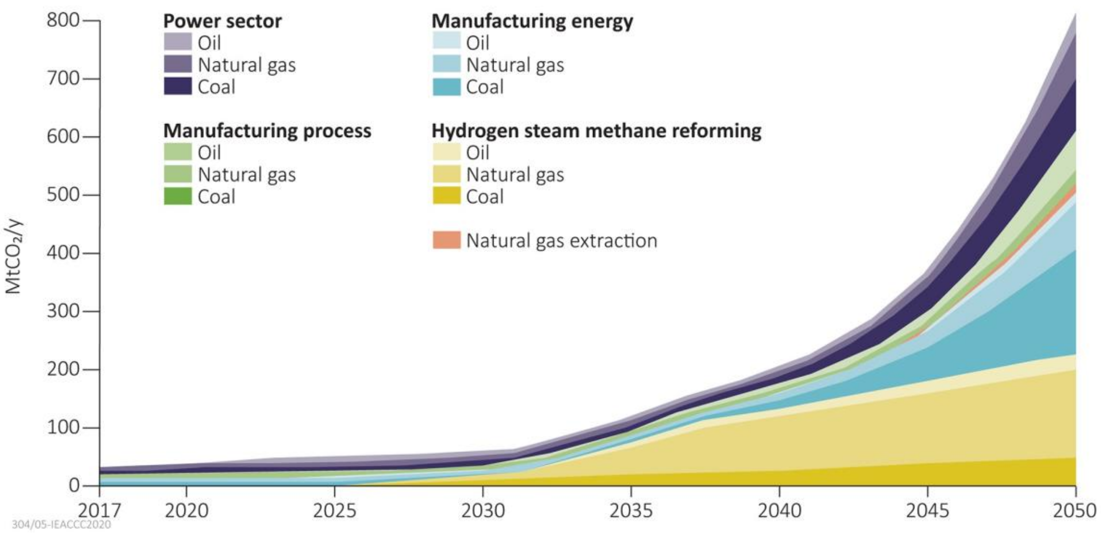


Figure 5 Global CO_2 emissions captured by CCUS (DNV GL, 2019)

2.1 COAL WITH CCUS

Looking specifically at what the IEA forecasts would mean for coal-related power generation, unabated coal use for power plants would need to reduce significantly, from around 2080 GWe in 2018 (IEA, 2019a) to below 150 GWe beyond 2045 for the 2DS scenario (IEA, 2017). For the SDS scenario, the reduction is higher, with virtually all generation from coal-fired power plants without CCUS phased out by 2030 in advanced economies and by 2045 in developing economies (IEA, 2019a), leaving coal accounting for less than 5% of power generation by 2040.

Recent analysis has indicated that CCUS availability has a large bearing on the extent of fossil fuel consumption in a climate constrained future (Budinis and others, 2018). A portion of the coal generation noted above would be replaced by coal power plant fitted with CCUS, peaking at around 350 GWe for both the 2DS and B2DS cases by around 2045, as shown in Figure 6 (IEA, 2017). Interestingly, the capacity of coal with CCUS decreases a little after 2045, as a typical capture efficiency of 85–95% still emits some CO_2 which is not consistent with a net zero emissions world, without emissions offset from biomass energy carbon capture and storage (BECCS) or increasing the level of CO_2 capture.

The more recent analysis by the IEA (2019a), indicates that around 170 GWe of coal plants are retrofitted with CCUS by 2050, primarily in China. This forms part of a strategy to either 'retrofit, repurpose or retire' existing coal power plant capacity. As part of this strategy, 720 GW of coal-fired power plant would reduce their operating hours to cut emissions, limiting electricity production but still providing system adequacy and flexibility. About one-quarter of the existing fleet would be retired in the SDS scenario before reaching the typical 50-year lifespan. This is in addition to about 600 GW of coal-fired power plants which retire as they reach or exceed their 50 year life span.

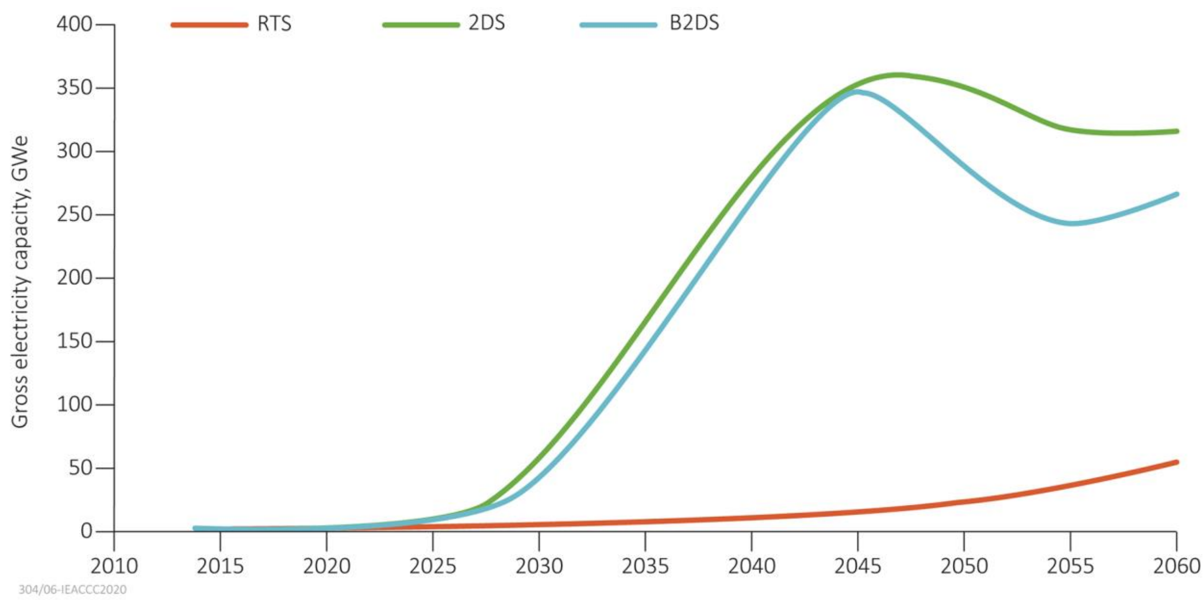


Figure 6 Coal with CCUS-related gross electrical power capacity (IEA, 2017)

A further factor in determining the actual extent to which unabated coal use will decline by 2050 and conversely to what extent coal with CCUS will increase over the same time frame, is the local geo-political situation. There are still around one billion people globally, primarily in Africa and Asia who do not have access to reliable electricity. As the living standards of such regions increase, they will seek to use indigenous energy sources such as solar, wind and biomass renewables, but also coal where this is available.

2.2 IS CCUS ON TRACK?

CCUS is not currently on track to achieve the levels of CO_2 reduction required by the 2DS, B2DS or SDS scenarios. The IEA's 'Tracking Clean Energy' progress indicator (IEA, 2017) provides a status snapshot of 39 critical energy technologies needed to stay within a 2°C temperature rise this century. Only seven of the technologies are assessed as being on-track, and CCUS is not one of them. For CCUS, the 2DS trajectory indicates a 2025 target of more than 400 $MtCO_2$/y stored by that date. However, the amount of CO_2 captured and stored in 2019 was around 38 $MtCO_2$, representing only 10% of the required 2025 level (*see* Section 4.1 for details). There have been some encouraging moves in the number of CCUS projects moving into the development pipeline since the IEA 2017 'Tracking Clean Energy' progress indicator, particularly in 2019. However, even if all of the CCUS projects in construction and in the current development pipeline were to come online, some of which are not due to be operational until the late 2020s or even the 2030s, the amount of CO_2 captured would be around 95–130 $MtCO_2$. This increases the amount of CO_2 captured to around 25–33% of the 2025 target, indicating the need for a significant increase in current investment levels.

If the Nationally Determined Contributions (NDCs) of the countries party to the Paris Agreement are anything to go by, the signs are not encouraging. As noted by various researchers (IEA, 2017; Dixon, 2018; Mills-Novoa and Liverman, 2019), CCUS is largely absent from the NDCs. Of the 189 NDCs submitted by 2017, only 11 mentioned CCUS. This suggests that whilst the case for CCUS appears to be clear, this has not been carried forward in the policies of the majority of nations. It should be noted however, that the NDCs have a relatively short-term focus with a five-year duration, so there is potential for CCUS to play a more significant role in the next rounds of NDC updates. There are more positive signs in the latest submissions of NDCs to the United Nations Framework Convention on Climate Change (UNFCCC) where 10 of the 13 strategies submitted by August 2019 included CCUS technologies (GCCSI, 2019a).

2.3 SUMMARY

The level of CCUS required to be fitted to coal-fired power generation plant by 2050 has reduced in the most recent forecasts, but the technology remains a key part of the energy transition to a net zero emissions future. However, the rate of CCUS capacity addition to capture the required level of CO_2 is not currently on track to deliver this, indicating the need for significant additional investment.

3 CCUS TECHNOLOGIES

Having reviewed the need for CCUS, this chapter gives a concise overview of the technologies encompassed by CCUS. At the basic level, CCUS prevents CO_2 from being released to the atmosphere. It involves capturing CO_2 produced by large power and industrial plants, compressing it for transportation and then either injecting it into rock formations underground, using it for EOR, or utilising the CO_2 to form useful products. CCUS as a technology is proven and understood, with carbon capture equipment used commercially to purify natural gas and other gases since as early as the 1930s. CO_2 was first injected underground in commercial-scale operations in 1972. It can be applied to fossil fuel power plant (both coal and natural gas fired) to provide low emissions generation capacity to complement intermittent renewable power sources (IEA, 2017; IChemE, 2018). The IEACCC has published many reports on CCUS; see for example (Lockwood, 2016, 2018a; Minchener, 2019).

There are three principal types of capture process:

Post-combustion capture – where CO_2 is removed from the flue gas after the main process conversion step (typically combustion step). The remaining flue gas is primarily nitrogen together with other minor components. Most post-process capture technologies used in demonstration projects today are amine-based absorption systems of the post-combustion capture type. Additional technologies that fall into the post-process capture category include:

- adsorption onto a solid sorbent;
- fuel cells, including molten carbonate fuel cells (MCFC); and
- membrane separation.

Oxyfuel combustion – where fuel is burned with oxygen in a stream of recycled CO_2. By excluding the nitrogen from the process, CO_2 separation becomes a relatively easy process of condensing out the water from the flue gas. However, it requires an air separation unit to produce the oxygen for the oxyfuel combustion process which adds to the system cost.

Pre-combustion capture – as in an integrated gasification combined cycle (IGCC) power plant in which the fuel is gasified/reformed to a $CO/H_2/CO_2$ mixture, typically incorporating a water-gas shift reaction step to increase the concentration of H_2 by reacting the CO with steam. The CO_2 is then captured from the pressurised fuel gas stream. The IGCC system combines chemical processing with power generation, with the flexibility of being able to produce H_2 which can be used for transportation fuel, as chemical feedstock or for power generation by direct combustion in a gas turbine or electrochemical conversion in a fuel cell. The typical separation technologies that fall into this category include:

- solvent separation processes such as Rectisol and Selexol;
- pressure swing adsorption; and
- water enhanced gas-shift.

Of the three approaches, post-combustion capture is the most widely used. In particular, chemical absorption using amines is utilised in two commercial-scale post-combustion capture facilities on coal-fired power plants, namely Boundary Dam and Petra Nova (*see* Section 4.3 for details).

3.1 CCUS COMPONENT READINESS LEVELS

The Technology Readiness Level (TRL) of a component or system qualitatively assesses the maturity of technology through the different stages of research and development (R&D). Of the different CCUS technologies at varying stages of development (Figure 7) most are at the pilot plant stage (TRL6) or higher (IChemE, 2018). There are a number of technologies for capture, transport and storage that are readily deployable at commercial scale (TRL9), which in the context of the IChemE study is defined as capturing over 0.4 $MtCO_2$/y. Several other technologies that can reduce costs and increase efficiency are at TRL7–8 and most should, in time, move to TRL9.

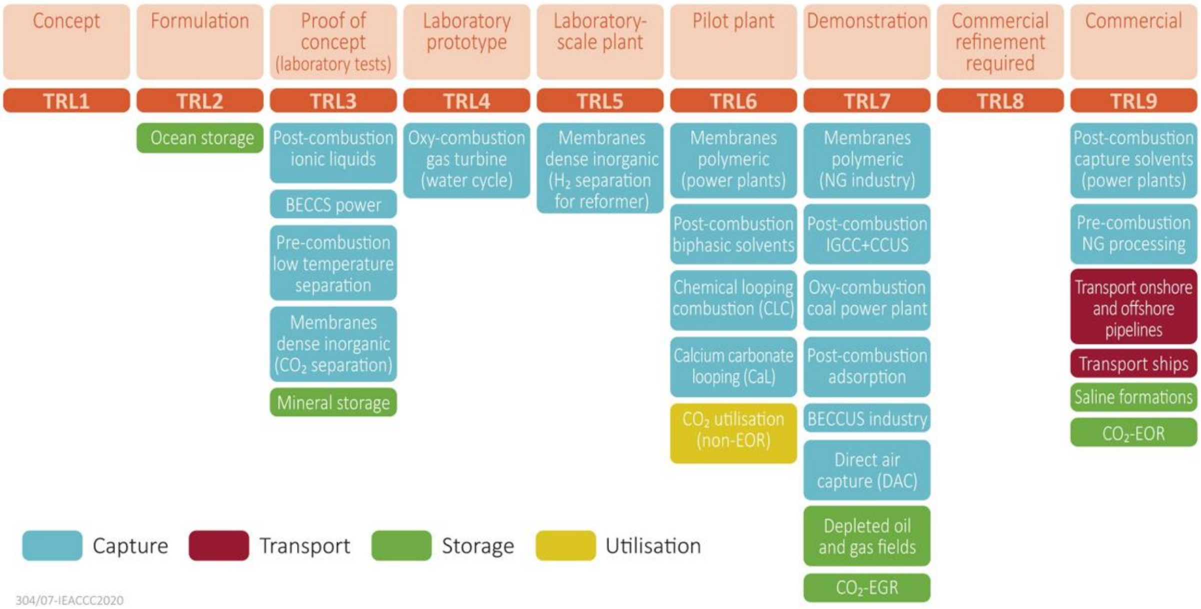


Figure 7 CCUS components in terms of technology readiness level (IChemE, 2018)

Therefore, the elements of the CCUS technology chain are in place for commercial deployment and their safety and operability has been confirmed in various demonstrations and commercial operations. This indicates that the barriers to widespread large-scale deployment of CCUS are not technical and that there is the potential for future cost reductions through next generation technologies as well as through the learning by doing cost reduction covered later in Section 5.1.

3.1.1 CCUS R&D priorities

A recent study in the UK sponsored by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS), looked to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. Using an analytical methodology developed by BEIS, the study took a system-level approach and valued innovations in a technology in terms of the system-level benefits a technology innovation provides. The part of the study which focused specifically on CCUS (EINA, 2019), defined the following as key priority development areas for CCUS:

- **For pre-combustion** – advanced reformer technologies to unlock the potential to combine hydrogen production with CCUS for power, which opens further opportunities across the energy system. Cost reduction is possible using cheaper and more energy-efficient materials and processes.
- **For post-combustion** – R&D into new solvent and absorption processes aimed at lowering cost and improving capture performance, whilst also having the potential to reduce regeneration costs, corrosion effects, environmental impact, and product degradation.
- **For oxyfuel combustion** – new technologies for lower-cost air separation in oxycombustion, including ion transport membranes (ITMs). Ceramic materials that conduct oxygen ions at elevated temperatures are an early-stage technology with significant potential for a step-change cost reduction in air separation. A review of the current status of oxyfuel combustion based on the Callide project is provided by Spero and Yamada (2018).

An in-depth analysis by Mission Innovation and the US DOE assessed the current gaps in CCUS technologies and identified the most promising directions for basic research needed to achieve long-term global carbon management (Mission Innovation, 2017; US DOE, 2017). This assessment defined Priority Research directions in the four areas of Capture, Utilisation, Storage and Cross-cutting topics, as summarised in Table 1.

TABLE 1 CCUS PRIORITY RESEARCH DIRECTIONS (MISSION INNOVATION, 2017)

Capture

- Designing high-performing solvents for CO_2 capture
- Creating environmentally friendly solvent processes for CO_2 capture
- Designing tailor-made sorbent materials
- Integrating sorbent materials and processes
- Understanding transport phenomena in membrane materials
- Designing membrane system architectures
- Catapulting combustion into the future
- Producing hydrogen from fossil fuels with CO_2 capture

Utilisation

- Designing complex interfaces for enhancing hydrocarbon recovery with carbon storage
- Valorising CO_2 by breakthrough catalytic transformations into fuels and chemicals
- Creating new routes to carbon-based functional materials from CO_2
- Designing and controlling molecular-scale interactions for electrochemical and photochemical conversion of CO_2
- Harnessing multiscale phenomena for high-performance electrochemical and photochemical transformation of CO_2
- Accelerating carbon mineralisation by harnessing the complexity of solid–liquid interfaces
- Tailoring material properties to enable carbon storage in products
- Tailoring microbial and bio-inspired approaches to CO_2 conversion
- Hybridising electrochemical and biological process for CO_2 conversion to fuels, chemical, and nutrients

Storage

- Advancing multiphysics and multiscale fluid flow to achieve Gt/y capacity
- Understanding dynamic pressure limits for Gt-scale CO_2 injection
- Optimising injection of CO_2 by control of the near-well environment
- Developing smart convergence monitoring to demonstrate containment and enable storage site closure
- Realising smart monitoring to assess anomalies and provide assurance
- Improving characterisation of fault and fracture systems
- Achieving next-generation seismic risk forecasting
- Locating, evaluating, and remediating existing and abandoned wells
- Establishing, demonstrating and forecasting well integrity

Cross-cutting

- Integrating experimental, simulation, and machine learning across multiple length scales to guide materials discovery and process development
- Coupling basic science and engineering for intensified carbon capture, purification, transport, utilisation and storage processes
- Incorporating social aspects into decision-making
- Developing tools to integrate life-cycle technoeconomic, environmental, and social considerations to guide technology portfolio optimisation

3.2 SUMMARY

The various elements of the CCUS technology chain are in place for commercial deployment, indicating that the barriers to widespread large-scale deployment of CCUS are not technical. Several other next generation technologies that could provide step change cost reductions and increase efficiency are being researched and developed and could, in time, reach the market.

4 STATUS OF CCUS

4.1 OVERALL GLOBAL POSITION

CCUS currently plays a relatively small role in power generation, with two operational power plants providing a combined 350 MWe capability. Both are retrofits of coal-fired power plants located in North America, namely:

- 110 MW Boundary Dam power plant in Canada, which was retrofitted with CO_2 capture in 2014 and is rated at 1.0 $MtCO_2/y$ captured;
- 240 MW side-stream at the Petra Nova power plant in Texas, USA, which started operation in January 2017, rated at 1.4 $MtCO_2/y$ captured.

These power plants continue to play a leading role in the total of 21 operational (June 2020) CCUS facilities globally as shown in Figure 8, with details of the facilities provided in Table 2 (GCCSI, 2019a). The majority of these facilities relate to natural gas processing applications, with the potential to store around 39–40 $MtCO_2/y$. In addition to these operational facilities, a further three are in construction due to be completed in the 2020s, with 16 in advanced development using a predominantly front end engineering design (FEED) approach and a further 19 projects in the early stages of development. The database includes 39 pilot- and demonstration-scale CCUS facilities (operating or about to be commissioned) with a further nine CCUS technology test centres (Quale and others, 2017).

A further list of CCUS projects is provided by the US National Energy Technology Laboratory's CCUS Database (NETL, 2018), which includes summary information and project links.

The key regions in terms of CCUS installations are clearly North America, Europe, the Middle East and Asia Pacific (including Australia), with activities in these regions highlighted in Section 4.2. The specific coal-fired CCUS cases of Boundary Dam and Petra Nova are covered in more detail in Section 4.3.

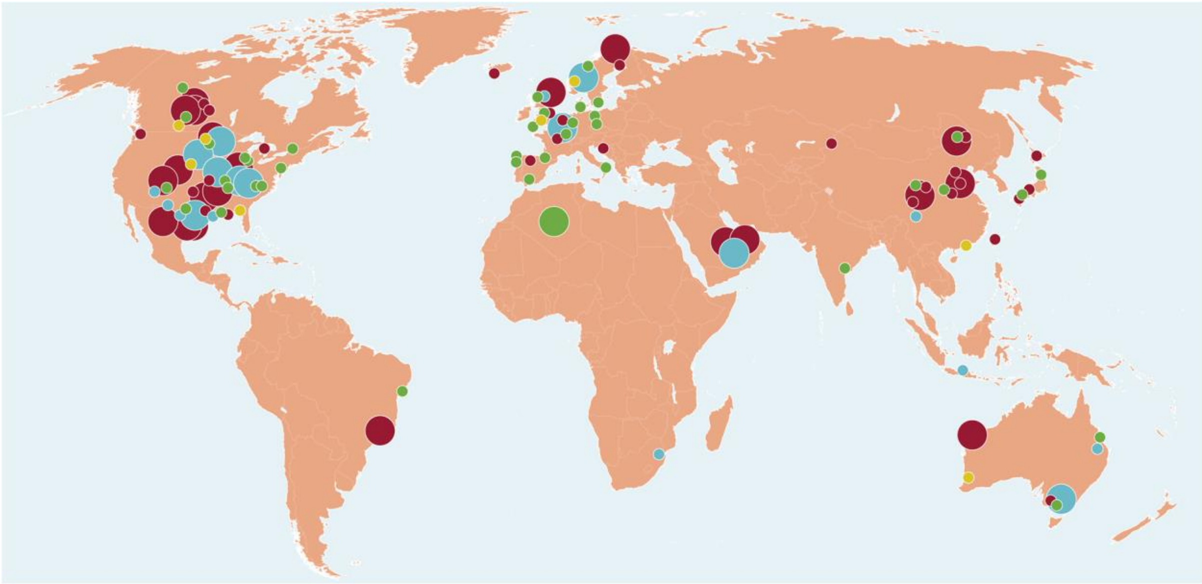


Figure 8 Global CCUS installations (GCCSI, 2019a)

TABLE 2 GLOBAL CCUS INSTALLATIONS (GCCSI, 2019A; GCSSI, 2019B)

No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Capture type	Storage type
1	Gorgon Carbon	Operating	Australia	2019	Natural gas processing	3.4–4.0	Industrial separation	Dedicated geological storage
2	Jilin Oil Field CO_2-EOR	Operating	China	2018	Natural gas processing	0.6	Industrial separation	EOR
3	Illinois Industrial Carbon Capture and Storage	Operating	USA	2017	Ethanol production	1.0	Industrial separation	Dedicated geological storage
4	Petra Nova Carbon Capture	Operating	USA	2017	Power generation	1.4	Post-combustion capture	EOR
5	Abu Dhabi CCUS (Phase 1 was Emirates Steel Ind)	Operating	UAE	2016	Iron and steel	0.8	Industrial separation	EOR
6	Quest	Operating	Canada	2015	Hydrogen for oil refining	1.0	Industrial separation	Dedicated geological storage
7	Uthmaniyah CO_2-EOR Demonstration	Operating	Saudi Arabia	2015	Natural gas processing	0.8	Industrial separation	EOR

TABLE 2 – CONTINUED

No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Capture type	Storage type
8	Boundary Dam CCS	Operating	Canada	2014	Power generation	1.0	Post-combustion capture	EOR
9	Petrobras Santos Basin Pre-Salt Oil field CCS	Operating	Brazil	2013	Natural gas processing	3.0	Industrial separation	EOR
10	Coffeyville Gasification Plant	Operating	USA	2013	Fertiliser production	1.0	Industrial separation	EOR
11	Air Products Steam Methane Reformer	Operating	USA	2013	Hydrogen for oil refining	1.0	Industrial separation	EOR
12	Lost Cabin Gas Plant	Operating	USA	2013	Natural gas processing	0.9	Industrial separation	EOR
13	Century Plant	Operating	USA	2010	Natural gas processing	8.4	Industrial separation	EOR
14	Snøhvit CO_2 Storage	Operating	Norway	2008	Natural gas processing	0.7	Industrial separation	Dedicated geological storage
15	Great Plains Synfuels Plant and Wyrburn-Midale	Operating	USA	2000	Synthetic natural gas	3.0	Industrial separation	EOR
16	Sleipner CO_2 Storage	Operating	Norway	1996	Natural gas processing	1.0	Industrial separation	Dedicated geological storage
17	Shute Creek Gas Processing Plant	Operating	USA	1986	Natural gas processing	7.0	Industrial separation	EOR
18	Enid Fertiliser	Operating	USA	1982	Natural gas processing	0.7	Industrial separation	EOR
19	Terrell Natural Gas Processing Plant (formerly Val Verde)	Operating	USA	1972	Natural gas processing	0.4–0.5	Industrial separation	EOR
20	Alberta Carbon Trunk Line (ACTL) with Sturgeon Refinery CO_2 Stream	Operating	Canada	2020	Hydrogen for oil refining	1.2–1.4	Industrial separation	EOR
21	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream	Operating	Canada	2020	Fertiliser production	0.3–0.6	Industrial separation	EOR
22	Sinopec Qilu Petrochemical CCS	Construction	China	2020-21	Chemical production	0.4	Industrial separation	EOR

TABLE 2 – CONTINUED

No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Capture type	Storage type
23	Yanchang Integrated CCS Demonstration	Construction	China	2020-21	Chemical production	0.4	Industrial separation	EOR
24	The ZEROS Project	Construction	USA	Late 2020s	Power generation	1.5	Oxyfuel	EOR
25	Wabash CO_2 Sequestration	Advanced development	USA	2022	Fertiliser production	1.5–1.8	Industrial separation	Dedicated geological storage
26	Port of Rotterdam CCUS Backbone Initiative (Porthos)	Advanced development	The Netherlands	2023	Various	2.0–5.0	Various	Dedicated geological storage
27	Norway Full Chain CCS	Advanced development	Norway	2023-24	Cement and waste-to-energy	0.8	Various	Dedicated geological storage
28	Lake Charles Methanol	Advanced development	USA	2024	Chemical production	4.2	Industrial separation	EOR
29	Abu Dhabi CCS Phase 2 – Natural Gas Processing Plant	Advanced development	UAE	2025	Natural gas production	1.9–2.3	Industrial separation	EOR
30	Dry Fork Integrated Commercial CCS	Advanced development	USA	2025	Power generation	3.0	Post-combustion capture	Dedicated geological storage & EOR
31	Carbonsafe Illinois-Macon County	Advanced development	USA	2025	Power generation and ethanol	2.0–5.0	Post-combustion capture and industrial separation	Dedicated geological storage & EOR
32	Project Tundra	Advanced development	USA	2025-26	Power generation	3.1–3.6	Post-combustion capture	Dedicated geological storage & EOR
33	Integrated Mid-Continent Stacked Carbon Storage Hub	Advanced development	USA	2025-35	Ethanol, power generation &/or refinery	1.9	Various	Dedicated geological storage & EOR
34	CarbonNet	Advanced development	Australia	2020s	In evaluation	3.0	In evaluation	Dedicated geological storage
35	Mustang Station of Golden Spread Electric Cooperative	Advanced development	USA	Mid-2020s	Cement production	1.5	In evaluation	In evaluation

TABLE 2 – CONTINUED

No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Capture type	Storage type
36	Prairie State Generating Station	Advanced development	USA	Mid-2020s	Power generation	6.0	Post-combustion capture	Dedicated geological storage
37	Gerard Gentleman Station	Advanced development	USA	Mid-2020s	Power generation	3.8	Post-combustion capture	In evaluation
38	San Juan Generating Station	Advanced development	USA	2023	Power generation	6.0	In evaluation	EOR
39	Cal Capture	Advanced development	USA	2024	Power generation	1.4	Post-combustion capture	EOR
40	Plant Daniel	Advanced development	USA	Mid-2020s	Power generation	1.8	Post combustion capture	Dedicated geological storage
41	Oxy and White Energy Ethanol EOR Facility	Early development	USA	2021	Ethanol production	06–0.7	Industrial separation	EOR
42	Hydrogen 2 Magnum (H2M)	Early development	Netherlands	2024	Power generation	2.0	In evaluation	Dedicated geological storage
43	The Clean Gas Project	Early development	UK	2024-25	Power generation	1.7–2.0	Post-combustion capture	Dedicated geological storage
44	Caledonia Clean Energy	Early development	UK	2025	Power generation	3.0	Post-combustion capture	Dedicated geological storage
45	Oxy and Carbon Eng Direct Air Capture and EOR Facility	Early development	USA	2025	–	1.0	Direct air capture	EOR
46	South West Hub	Early development	Australia	2025	Fertiliser production & power generation	2.5	Industrial separation	Dedicated geological storage
47	Hynet North West	Early development	UK	Mid--2020s	Hydrogen production	2.0	Industrial separation	Dedicated geological storage
48	ECO2S: Early CO_2 Storage Complex in Kemper County	Early development	USA	2026	In evaluation	3.0	In evaluation	Dedicated geological storage
49	Northern Gas Network (H21), UK	Early development	UK	2026-28	Hydrogen production	1.5–20.0	Industrial separation	Dedicated geological storage

TABLE 2 – CONTINUED								
No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Capture type	Storage type
50	Ervia Cork CCS	Early development	Ireland	2028	Power generation and hydrogen production	2.5	In evaluation	Dedicated geological storage
51	China Resources Power (Haifeng) Integrated CCS Demo	Early development	China	2020s	Power generation	1.0	Post-combustion capture	Dedicated geological storage
52	Huaneng Greengen IGCC (Phase 3)	Early development	China	2020s	Power generation	2.0	Post-combustion capture	In evaluation
53	Korea-CCS 1&2	Early development	S Korea	2020s	Power generation	1.0	Post-combustion capture	Dedicated geological storage
54	Sinopec Shengli Power Plant CCS	Early development	China	2020s	Power generation	1.0	Post-combustion capture	EOR
55	Net Zero Teesside	Early development	UK	2020s	Various	0.8–10.0	Various	Dedicated geological storage
56	Acorn Scalable CCS	Early development	UK	2020s	Various	3.0–4.0	In evaluation	Dedicated geological storage
57	Drax BECCS	Early development	UK	2027	Power generation	4.0	Post-combustion capture	Dedicated geological storage
58	LafargeHolcim Cement Carbon Capture	Early development	USA	Mid-2020s	Chemical production	0.7	In evaluation	EOR
59	Velocys' Bayou Fuels Negative Emission	Early development	USA	2024	Chemical production	0.5	In evaluation	Dedicated geological storage

4.2 REGIONAL IMPACT

4.2.1 North America

Twelve of the 19 large-scale CCUS operating facilities are located in North America, due in large part to supportive national policy frameworks, accessible CO_2 storage sites and strong stakeholder support including the private sector. North America hosts both of the coal-fired power plant CCUS projects, which are discussed in Section 4.3.

USA – In the USA, Section 45Q of the Internal Revenue Code which provides tax credits for storage of CO_2 was extended in 2018 for projects commencing construction by 2024. The tax credit now increases linearly each year to a maximum of 50 US$/t$CO_2$ for saline aquifer-based geological storage or 35 US$/t$CO_2$ for EOR by 2026, tracking inflation thereafter. Seen as the most progressive CCUS-specific incentive, further details of this financial instrument are provided in Section 6.1.1.

At the state level, California has passed a zero-carbon electricity mandate and set a goal to be carbon-neutral by 2050, which has been followed by six further states now having 100% carbon-free energy goals in their electricity markets. States including Montana, Louisiana, Texas, and North Dakota provide tax incentives for CCUS deployment, while others like Wyoming, aim to make substantial progress with CCUS.

In addition, the Low Carbon Fuel Standard (LCFS) is a credit-based trading mechanism that aims for a 20% reduction in the intensity of California's transportation fuels by 2030 (Townsend and Havercroft, 2019). It places lifecycle carbon intensity targets on all transportation fuels sold in California, with the aim of diversifying the fuel mix, reducing dependency on petroleum, and reducing emissions of GHG and other air pollutants. Fuels that have a lower carbon intensity than the carbon intensity target generate credits and fuels with a higher carbon intensity generate deficits. In 2018, the LCFS was amended to enable CCUS projects that reduce emissions associated with the production of transport fuels sold in California and projects that directly capture CO_2 from the air, to generate LCFS credits. Trading in 2019 at an average of 194 US$/t$CO_2$, the credit applies to CCUS projects that lower the emissions intensity of fuels in the California market.

The USA is well placed to continue to play a leading role in the global roll-out of CCUS as:

- The power sector accounts for 28% of their greenhouse gas emissions, with around half of total new generation capacity between now and 2050 likely to come from NGCC-based fossil fuel-fired power (EIA, 2019). An analysis of 45Q tax credits has shown that it could spur retrofits of coal and natural gas power plants, capturing a potential 49 MtCO_2/y by 2030 (Nagabhushan and Thompson, 2019).
- The US industrial sector accounts for another 22% of total emissions, from sources including ethanol production and natural gas processing. Such facilities could be ideal targets for low cost CCUS commercialisation and technology optimisation.

Canada, Central and South America – Interest in CCUS deployment remains strong across the Americas outside the USA:

- Canada's Government together with BHP, Occidental Petroleum and Chevron are investing CAN$25 million in Carbon Engineering, a Canadian Direct Air Capture (DAC) company, through Canada's Strategic Innovation Fund.

- Petrobras Santos Basin Pre-Salt Oil Field CCUS in Brazil has been separating CO_2 as part of natural gas processing since 2013, storing 3 Mt/y, with the captured CO_2 injected into oil fields for EOR. Stakeholders are keen to speed up CCUS use mainly in coal and natural gas power plants, but also in the ethanol sector.
- With funding from the World Bank CCUS Trust Fund, two CCUS pilot projects are progressing in Mexico, namely the CO_2 Capture Pilot Project (CCPP) and the CO_2 EOR and Storage Pilot Project (CESP). Significant planning and scoping have already been completed and the projects are due to proceed in 2020.

4.2.2 Europe

In Europe, CCUS is still considered necessary to achieve net zero GHG emissions by 2050, although at a lower level than previously thought, due to the rapid deployment of renewable energy technologies and issues concerning social acceptance of the CCUS technology itself (EU, 2018; Silva and others, 2019). CCUS remains as one of the EU's seven strategic building blocks to achieve net zero GHG, with CCUS deployment required especially in energy-intensive industries and for the production of carbon-free hydrogen as part of the energy transition. CCUS will also be essential if CO_2 emissions from biomass-based energy and industrial plants are to be captured and stored to create negative emissions. Considering that a plant that is built today will likely still be operational in 2050, the ability to roll-out carbon removal technologies increases the credibility of the EU's strategy.

The way CCUS projects are planned in Europe has changed considerably during the last decade; now the focus is on the 'hub and cluster' approach. Capturing CO_2 from clusters of industrial installations, instead of single sources, and using shared infrastructure for the subsequent CO_2 transportation and storage network, will drive down unit costs across the CCUS value chain. Keeping a network open for third party CO_2 injections increases economies of scale. Using a mix of transportation including pipelines, ships, trains and trucks offers flexibility and accessibility to a wider range of CO_2 sources around the industrial clusters. Several major industrial regions are planning CCUS cluster developments, with a few examples being:

- **Netherlands** – Port of Rotterdam (Porthos, 2019) which aims to capture 2–5 $MtCO_2$/y primarily from industrial sources. It continues CCUS activities in the region following the ROAD project (Read and Kombrink, 2018) which was cancelled in 2017 after the withdrawal of Uniper and Engie. The ROAD project design applied post-combustion technology to capture the CO_2 from a new 1069 MWe coal-fired power plant (Maasvlakte Power Plant 3), with the capture unit having a design capacity of 250 MWe equivalent. Project Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage and involves the construction of a CO_2 transport and storage infrastructure, totalling around 55 km in length, between the Port of Rotterdam and depleted gas fields beneath the North Sea.

- **Norway** – The Northern Lights project is part of the Norwegian full-scale CCUS project which includes capture of CO_2 from industrial sources in the Oslo region and shipping of liquid CO_2 from these industrial capture sites to a subsea storage location in the North Sea, for permanent geological storage. The solution being considered will have an initial storage capacity of around 1.5 $MtCO_2/y$ (Northern Lights, 2019).
- **UK – Humber and Teesside** – The Teesside cluster includes a commercial-scale natural gas combined cycle (NGCC) power plant equipped with CCUS, which is planned to be the anchor project for the cluster. Now named Net Zero Teesside (NZT, 2019), it is one of five global CCUS hubs part-funded through the Oil and Gas Climate Initiative's CCUS KickStarter programme (OGCI, 2019). The Zero Carbon Humber Cluster Pilot is planned to be anchored by the proposed BECCS project at the 3.8 GWe Drax facility, the UK's largest power station (ZCH, 2019). Initially the project will include CCUS on one of the four 100% biomass-fired pulverised fuel boilers by 2027, which were converted previously from coal to biomass firing. The project will generate negative 4 $MtCO_2/y$, with the addition of CCUS to all four biomass boilers by 2035, generating negative 16 $MtCO_2/y$. Testing of CCUS, based on C-Capture's post-combustion solvent technology on a side stream at Drax is already in progress.

4.2.3 Middle East and Central Asia

Middle East **–** The focus of CCUS activities in this region is for natural gas processing and the growing industrial and petrochemicals sectors. With accessible underground CO_2 storage potential, abundant gas resources and hydrogen production facilities with excess capacity, the Middle East has potential to become an important region for CCUS development and deployment. Saudi Arabia and the UAE lead this region's efforts, hosting the Abu Dhabi CCUS and Uthmaniyah CO_2-EOR large-scale CCUS facilities. Both are supported and operated by state-owned enterprises, with the CO_2 being used for EOR.

Central Asia **–** Energy demand is increasing in Central Asia, driven by a growing population and increasing standard of living. It is likely to be met using indigenous fossil fuels. As the region contains some of the world's most energy-intensive economies, achieving global CO_2 will require significant decarbonisation, with CCUS playing a potentially important role. In Kazakhstan for example, fossil fuels contribute 98% of the country's primary energy supply with coal contributing 44% (IEA, 2019b). The country is interested in CCUS, given its significant coal reserves and dependence on mining. A natural resources company, Eurasian Resources Group is currently exploring how to use CCUS to reduce emissions from its fossil fuel power generation fleet.

4.2.4 Asia Pacific

The Asia Pacific region accounts for more than 50% of global CO_2 emissions, driven by rapidly growing 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 352 GW of coal-fired power plants under construction or in planning. In 2017, the Asia Pacific region was responsible for 72% of global coal consumption, with China alone contributing 48%. Increasing coal power generation in Indonesia, Bangladesh, Philippines and Vietnam is driving future forecast demand. The general lack of legal and regulatory regimes to incentivise CCUS investment in the region could make large-scale adoption of CCUS challenging, although the GCCSI projects database shows that the Asia Pacific region is one the most active in terms of CCUS, with 12 large-scale facilities either operating or in various stages of development (GCCSI, 2019b).

China – China leads the region's CCUS activities with one large-scale facility in operation, two in construction and five in early development (*see* Table 2). In terms of CO_2 emissions, it contributes almost one third of global emissions. 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 employment. Their new National CCUS Professional Committee will provide government with support and advice, aiming to enhance international cooperation on CCUS. In May 2019, the latest Roadmap for CCUS in China was published (Guo and Huang, 2020). 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. Whilst the GCCSI expects these policy commitments to advance the deployment of CCUS (GCCSI, 2019a), a previous comprehensive study of CCUS in China (Lockwood, 2018b) concluded that from a cost perspective, China could realistically proceed to retrofit a significant portion of the country's coal fleet by 2035, provided that adequate policy incentives were introduced. However, more recent analysis (Jiang and others, 2020) indicates that China's CCUS policy is insufficient for further development of CCUS technology, citing lack of an enforceable legal framework, insufficient information for the operation of projects, weak market stimulus and a lack of financial subsidies. A further analysis (Fan and others, 2020) indicated that CCUS retrofit of coal-fired power plant could only become viable from an investment viewpoint if the decarbonised electricity price increased to 0.75 ¥/kWh (around 0.1 US$/kWh), equal to the feed-in tariff of solar photovoltaic and biomass power, when the investment value could exceed that of wind power generation projects in China.

India – In 2018, India's emissions rose by 4.8%, as a result of a strong increase in energy demand, with coal use increasing by 5%. It has the world's third largest coal fleet, with an average plant age of 16 years. However, despite the significant potential for India to contribute to global CO_2 emissions reduction, there are no projects in India listed in the GCCSI database of current and planned projects (*see* Table 2). A recent analysis of CCUS in India (Gupta and Akshoy, 2019) noted that there is marginal interest in the domestic demonstration of CCUS technology in India, due mainly to concerns over public reaction to underground CO_2 storage and in particular a relatively poor understanding of geological CO_2 storage data in India. A comprehensive national study on Indian storage basins is therefore needed to support the potential for CCUS demonstration in India. India has however played an active role in international collaborations in the area of CCUS (Lockwood, 2018a).

Japan – The Japanese Ministry of Economy, Trade and Industry (METI) and the Ministry of the Environment (MOEJ) continue to drive Japan's CCUS programme (Suzuki, 2018). The programme addresses the full CCUS value chain including the development and demonstration of capture technologies, investigating regulatory models, exploring policy options for commercial deployment, identifying and characterising storage reservoirs and CO_2 transport options, together with understanding CCUS business models. The Japanese Government submitted recently its Long-Term Strategy under the Paris Agreement, to the UNFCCC. The strategy identifies CCUS alongside other technologies to reduce emissions, including the production of clean hydrogen. It 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 CCUS deployment (GCCSI, 2019a). The Hydrogen Energy Supply Chain project (HESC) is a significant example of Japanese government collaboration with the private sector and other governments to commercialise CCUS (HESC, 2018). This project is being developed by Kawasaki Heavy Industries, Electric Power Development Co (J-Power), Iwatani Corporation, Marubeni Corporation, Sumitomo Corporation and AGL, with the support of the Governments of Japan, Australia and the State of Victoria and will produce liquefied hydrogen from brown coal in the Latrobe Valley for export to Japan. In the pilot phase around half a billion dollars will be invested in Australia and Japan. If successful, an investment decision to construct a commercial scale clean hydrogen production facility with CCUS in the Latrobe Valley, to supply Japan could be made in the mid-2020s. Other key CCUS projects in Japan include:

- Toshiba Corporation's 49 MW Mikawa power plant as part of the 'Demonstration of Sustainable CCS Technology Project', which started in July 2016 under the sponsorship of MOEJ, to promote clean energy generation. It will be fuelled by biomass and coal with carbon capture and completion is expected in early 2020 (Kitamura, 2019).
- A new CO_2 capture plant was established in August 2019, continuing progress at the Osaki CoolGen facility. The JPOWER and Chugoku Electric Power Company's 166 MW oxygen-blown coal integrated gasification combined cycle (IGCC) facility commenced operation including separation and capture of CO_2 in December 2019. This is the second step of a three step project, with the final step due to add a fuel cell in order to conduct a demonstration of integrated coal gasification fuel cell combined cycle (IGFC) with CO_2 capture.
- Japan CCS's Tomakomai CCS Demonstration Project which achieved its target of injecting 300,000 tCO_2 into a formation 1000 m below the seabed in the harbour area of Tomakomai Port, as well as an experimental injection into a formation 2400 m under the seabed. Following the successful achievement of this target in November 2019, injection was suspended although monitoring operations will be continued to assess the behaviour of the injected CO_2. The project aimed to demonstrate the viability of the full chain CCUS system using CO_2 captured via pressure swing absorption system from a hydrogen production unit on an oil refinery local to the port (Sawada and others, 2018).

Australia – Australia is in a good position to progress CCUS, with a well-developed legal and regulatory framework, and over 400 Gt of geological storage capacity potentially available. Key CCUS projects include:

- Gorgon project which when fully operational will be the world's largest dedicated geological storage facility (Gorgon, 2019);
- HESC pilot project in the Latrobe Valley, as noted above, in partnership with Japan; and
- CarbonNet project which will investigate the feasibility for a commercial-scale, multi-user CCS network in Gippsland, Victoria, jointly funded by the Australian and Victorian Governments to 2020, with support from the GCCSI. It includes field investigation activities such as geophysical and geotechnical surveys.

4.2.5 Recent CCUS project announcements

The US DOE has announced nine new FEED projects for coal- and natural gas-based CCUS projects in the USA (US DOE, 2019), as shown in Table 3. The selected projects will receive US$55.4 million in federal funding for cost shared R&D under the funding opportunity announcement (FOA) award, 'Front end engineering design (FEED) studies for carbon capture systems on coal and natural gas power plants'. The selected projects will support FEED studies for commercial-scale carbon capture systems and have now been added to the CO2RE Database (GCCSI, 2019b) and are shown in Table 3.

TABLE 3 RECENT FEED STUDIES FUNDED BY US DOE (US DOE, 2019)

Project	Awardee	Details
FEED Study for Retrofitting a 2 x 2 x 1 Natural Gas-Fired Gas Turbine Combined Cycle Power Plant for Carbon Capture Storage/Utilisation	Bechtel National (Reston, VA)	FEED study for a retrofit carbon capture and compression plant add-on to Panda Energy Fund's existing NGCC power plant in Texas. The post-combustion capture plant is an amine-based conventional absorber-stripper scrubbing system with a non-proprietary solvent. The open-access and open-technology approach is to facilitate global understanding of a carbon capture plant that is ready to install at existing power plants.
Full-Scale FEED Study for Retrofitting the Prairie State Generating Station with an 816 MWe Capture Plant Using MHI Post-Combustion CO_2 Capture Technology	University of Illinois (Champaign, IL)	FEED study for the installation of a CCS facility at the Prairie State Generating Company's Energy Campus in Marissa, Illinois. The project will be based on the Advanced KM CDR Process™ CO_2 capture technology from MHI. The project team that successfully completed the Petra Nova capture plant has been reassembled to benefit from lessons learned. The Advanced KM CDR Process is an amine-based capture system that uses the KS-21 solvent. If successful, the project would provide valuable insight into lowering the cost of carbon capture systems.

TABLE 3 – CONTINUED

Project	Awardee	Details
FEED Study for Retrofit Post-Combustion Carbon Capture on a NGCC Power Plant	Electric Power Research Institute (Palo Alto, CA)	FEED study to determine the technical and economic feasibility of retrofitting California Resources Corporation's 550 MWe Elk Hills Power Plant (EHPP), located in Kern County, California, with a post-combustion carbon capture technology. The project will use Fluor's amine-based Econamine FG Plus process to capture 75% of the CO_2 produced by the EHPP. Overall, about 4000 t of CO_2 per day could be captured and delivered for use in EOR. If the technologies used in this project are successfully implemented, many existing US-based plants could be retrofitted.
Large-Scale Commercial Carbon Capture Retrofit of the San Juan Generating Station	Enchant Energy (New York, NY)	Site-specific FEED study for retrofitting the San Juan Generating Station in Waterflow, New Mexico, with CCUS technology, in collaboration with the City of Farmington, New Mexico. The FEED study will allow Enchant Energy to determine the technical and economic viability of extending the life of an existing plant using a CCUS system. If successful, a CCUS retrofit of the existing San Juan Generating Station could reduce significant CO_2 emissions per year.
Commercial Carbon Capture Design & Costing: Part Two	Ion Engineering (Boulder, CO)	FEED study for the installation of Ion Engineering advanced carbon capture system retrofitted to Nebraska Public Power District's Gerald Gentleman Station near Sutherland, Nebraska. Ion Engineering will expand upon its solvent-based CO_2 capture technology by utilising their ICE-21 solvent that offers key technical advantages including greater reduction in energy, lower emissions, faster solvent kinetics, and less solvent degradation to minimise the need for solvent replacement. The project has the potential to provide data and insight into the deployment of their CO_2 capture technology and realistic cost expectations.
Commercial-Scale FEED Study for MTR's Membrane CO_2 Capture Process	Membrane Technology and Research Inc (Newark, CA)	FEED study of a membrane-based CO_2 capture system at Basin Electric's Dry Fork Station near Gillette, Wyoming. The study will build on previous DOE-funded research that determined the membrane process can capture CO_2 in the 40 $/t range while offering compact size, environmental friendliness, low water usage and no disruption to the existing steam cycle. If successful, this study would provide a pathway for large commercial deployment of this advanced membrane-based capture technology.
FEED: Project Tundra Carbon Capture System	Minnkota Power Cooperative Inc (Grand Forks, ND)	FEED study to install a post-combustion capture system at the Minnkota-operated (Square Butte Electric Cooperative-owned) Milton R. Young Station near Center, North Dakota. The project will use Fluor's Econamine FG Plus technology, an amine-based process specialised for the removal of CO_2 from low-pressure, oxygen-containing gas. This system offers improved efficiency, improved environmental and cost profile, and a low levelised cost of capture. The project will provide valuable technical insights into the economic business case for CCUS installed on an existing coal-fired power plant.

TABLE 3 – CONTINUED		
Project	Awardee	Details
FEED of Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Southern Company Natural Gas-Fired Power Plant	Southern Company Services (Birmingham, AL)	FEED study for the installation of a Linde-BASF aqueous amine solvent-based post-combustion CO_2 capture technology at an existing domestic natural gas-fired combined cycle power plant within Southern Company's portfolio of assets. The two sites considered are Alabama Power Company's Plant Barry in Bucks, Alabama and Mississippi Power Company's Plant Daniel located in Moss Point, Mississippi. The Linde-BASF technology is based on a typical lean-rich solvent absorption/regeneration cycle for CO_2 capture and leverages several innovative features for both solvent and process optimisation. This project will provide a reference case for understanding CO_2 capture technologies and the future development of cost-effective and environmentally sound systems.
Piperazine/Advanced Stripper Front End Engineering Design (PZAS FEED)	The University of Texas at Austin (Austin, TX)	FEED study for the Piperazine Advanced Stripper (PZAS) process for CO_2 capture at the Mustang Station of Golden Spread Electric Cooperative (GSEC) in Denver City, Texas. The PZAS is an advanced CO_2 scrubbing process with solvent regeneration for post-combustion carbon capture from natural gas flue gas. The project will provide insight on the benefits and economics of integrating CO_2 captured from a power station.

4.3 DETAILS OF BOUNDARY DAM AND PETRA NOVA

4.3.1 Boundary Dam

The Boundary Dam 3 project in Saskatchewan, Canada, was the world's first fully integrated CCUS facility at a coal-fired power plant. The nominal capture rate of the facility is 1 $MtCO_2/y$ and includes the capture, compression and transport elements for CO_2. Further, the CCUS facility is fully integrated with the coal power plant which provides all its steam and power requirements. The facility produces CO_2 primarily for EOR, but it is also provided for injection and permanent geological storage at Aquistore. This is an onsite CO_2 measurement, monitoring and verification project, which involves the injection and storage of CO_2 in a saline aquifer at a depth of 3400 m.

The Boundary Dam 3 project exceeded over 3 $MtCO_2$ captured towards the end of 2019 since it first opened (*see* Figure 9) with a diary of some of the significant plant events in the last two years of operation shown in Table 4.

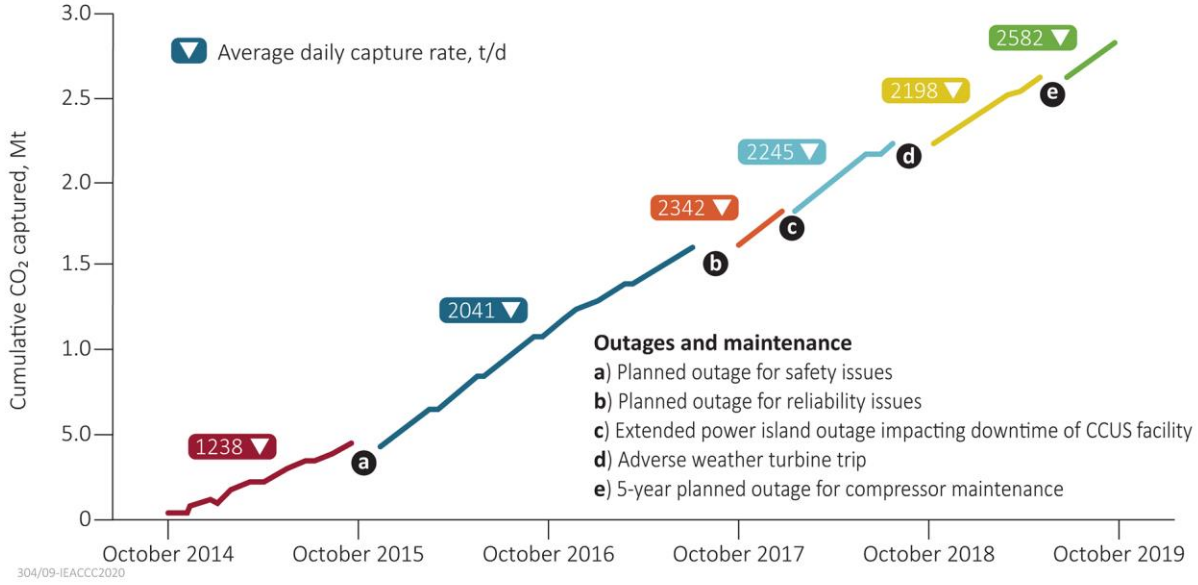
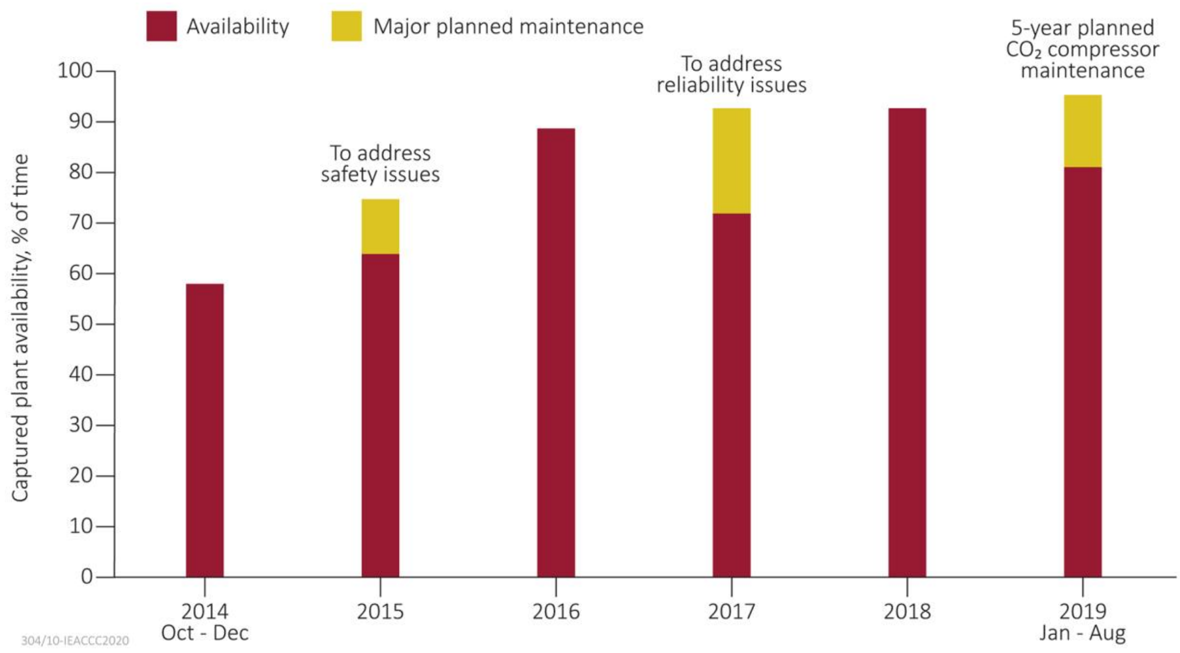


Figure 9 Cumulative CO_2 captured at Boundary Dam 3 (CIAB, 2019)

TABLE 4	DIARY OF CCUS FACILITY AVAILABILITY AND CO_2 CAPTURED AT BOUNDARY DAM 3 (2017-19) (MODIFIED BY AUTHOR)
December 2017 annual summary	CCUS Facility experienced lower than expected production in December 2017 due to extended maintenance at the power plant. Once power plant was returned to service, the CCUS Facility was back online shortly after and captured an average of 2506 tCO_2 per day for the remainder of the month. In total, 32,749 t were captured in December for a total of 506,848 t in 2017 and 1839,335 t since CCUS Facility operations began in 2014.
December 2018 annual summary	CCUS Facility captured 70,395 tCO_2 in December and was online 86.3% of the month coming offline for 102 hours due to a boiler tube leak on Boundary Dam Unit 3. In 2018, the CCUS Facility captured a total of 625,996 t, with the overall availability of 69% for the facility in 2018. Excluding the days when the CCUS Facility was available but offline due to issues at the Boundary Dam power plant itself (for example, days when the power plant was down due to storm damage during the summer), availability increased to 94%. This improvement in availability relative to 2017 is attributed to the improvements made during the 2017 planned maintenance outage. Amine usage for 2018 was also lower compared to 2017 and the previous years.
January 2019	CCUS Facility was online 84.4% of the month. The facility was offline for 77 hours due to boiler issues on the Boundary Dam Unit 3 power plant and a maintenance repair issue at the CCUS Facility. The CCUS Facility achieved a peak one-day capture rate of 2580 tCO_2, although the average daily capture rate was lower than the previous month due to amine issues limiting the amount of CO_2 that could be absorbed.
February 2019	CCUS Facility was online 96.5% of the month. The facility was offline for 23 hours due to boiler issues on Boundary Dam Unit 3 and a minor compressor issue at the CCUS Facility. With ongoing process improvements, the average daily capture rate increased from January.
March 2019	CCUS Facility was online 32% of the month. The facility was offline for part of month as part of a 60 day scheduled planned maintenance which began on 11 March.

TABLE 4 – CONTINUED	
April 2019	CCUS Facility was offline in April for planned maintenance, to include cleaning and inspecting the facility, disassembling the compressor and making minor mechanical repairs. Unit 3 at the Boundary Dam power station also underwent maintenance during this time.
May 2019	CCUS Facility returned to service on 7 May after a 58 day maintenance outage. After final compressor system checks, the facility returned to continuous service on 12 May. For the month of May, the CCUS Facility was online 65% of the month.
June 2019	CCUS Facility was online 99.4%, coming offline for only 4 hours due to a faulty valve on the compressor.
July 2019	CCUS Facility was offline in July, due to a severe storm that struck the power station on 14 June resulting in damage to Unit 3. During this time, routine and preventative maintenance was performed at the CCUS Facility.
August 2019	CCUS Facility was online 78.4% of the month coming offline for 161 hours to accommodate outages at the BD3 power station.
September 2019	The sulphuric acid plant was offline for most of September for upgrades. The CCUS Facility was online 83.4% of the month coming offline for 119 hours to accommodate outages at the BD3 power station.
October 2019	CCUS Facility was online 87.9% of the month coming offline for 43 hours to accommodate an outage at the BD3 power station and 48 hours for maintenance on the CCUS plant.
November 2019	CCUS Facility started a scheduled maintenance outage on 14 Nov 2019, reducing the monthly availability figure to 42.2% online for the month. In addition, the Sulphuric acid plant was offline for upgrades, so no acid was produced this month.
December 2019 annual summary	CCUS Facility returned to service on 7 December 2019 after the November 2019 scheduled outage. The facility captured a total of 616,119 tCO_2 for 2019 as a whole and has now exceeded 3 $MtCO_2$ captured in total since operation began in 2014.

The CCUS facility faced technical challenges, particularly in the early years, including some process complications relating to fly ash and other contaminants. Significant levels of amine degradation also occurred as a result of high temperatures due to poor steam temperature control, leading to amine reaction with flue gas contaminants and particulates. Major work was undertaken to address these issues between October 2015 and August 2017, including replacing some of the carbon steel infrastructure with stainless steel and the introduction of anti-fouling measures. As a result, analysis carried out by the International Knowledge Centre on behalf of the Coal Industry Advisory Board (CIAB, 2019) indicates that the facility has been able to achieve 85% availability levels since the end of 2017 as shown in Figure 10. This compares with a design availability for the CCUS facility of 85%, indicating that disregarding those plant outages outside the scope of the CCUS facility itself, the availability is now close to the target level.



Capture plant availability is the percentage of time the capture plant is capturing CO_2 while the power plant is operating at 50% load and above. The calculations include both the original planned maintenance durations as well as any unplanned extensions.

Figure 10 Availability of carbon capture facility at Boundary Dam 3 (CIAB, 2019)

4.3.2 Petra Nova

The Petra Nova Project is a commercial-scale post-combustion CO_2 capture project developed as a joint venture between NRG Energy (NRG) and JX Nippon Oil and Gas Exploration (Armpriester, 2017). The project is designed to separate and capture CO_2 from an existing coal-fired unit's flue gas slipstream at NRG's WA Parish Generation Station located near Houston, Texas. The captured CO_2 is transported by pipeline and injected into the West Ranch oil field for EOR purposes. The project, which is partially funded by financial assistance from the US DOE will use Mitsubishi Heavy Industries of America's Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) advanced amine-based CO_2 absorption technology to treat and capture at least 90% of the CO_2 from a 240 MW equivalent flue gas slipstream from Unit 8 of the power plant. The project is designed to capture around 5000 tCO_2/d, equivalent to 1.5 $MtCO_2/y$ captured, which represents currently the largest commercial-scale deployment of post-combustion CO_2 capture at a coal-fired power plant. The objectives for the Petra Nova CCUS project were to:

- demonstrate successful operation of the amine-based post-combustion capture process at 90% CO_2 capture efficiency up to 250 MWe scale;
- demonstrate technological advances aimed at lowering the energy requirements of the carbon capture process;
- demonstrate the concept of integrating a gas turbine-based cogeneration system to provide the steam and power requirements for the CCUS system;

- establish the impact of CCUS operations on the cost of electricity (COE) and provide recommendations necessary to demonstrate technology to achieve a COE increase of below 35% relative to the unabated power plant case.

The successful delivery of Petra Nova has demonstrated that the CCUS facility integration approach adopted works, and that a capture cost of 65 US$/t$CO_2$ in the Petra Nova-based configuration is achievable.

4.3.3 Comparison of Boundary Dam and Petra Nova approaches

There are similarities as well as several important differences between the Boundary Dam and Petra Nova CCUS facilities. Both plants use a post-combustion solvent-based CO_2 capture technology to remove about 85–90% CO_2 from the flue gas stream from one unit of the coal-fired power plant at which they are deployed. Both systems use advanced amines to separate CO_2 from the flue gas, Shell's Cansolv solvent at the Boundary Dam facility and Mitsubishi's KS-1 solvent at Petra Nova. The captured CO_2 in both plants is used predominantly for EOR, with Boundary Dam selling the CO_2 to a third party, whereas Petra Nova has a financial arrangement whereby it shares in the income from the sale of oil produced with the captured CO_2.

For the Boundary Dam project, one power plant unit was repowered to increase its efficiency prior to installing the CCUS facility, producing 160 MWe gross power output (110 MWe net power output with CO_2 capture). Petra Nova was not repowered; instead the capture system was retrofitted to a slip stream of flue gas from one of the existing units with an equivalent gross capacity of 240 MWe. At Boundary Dam, the main parasitic load for the CCUS facility's regeneration unit is supplied by low-pressure steam diverted from the main power plant steam cycle, which leads to a derating of the steam turbine power output. In contrast, the regeneration energy at Petra Nova is supplied by a natural gas-fired cogeneration power plant producing steam plus 70 MWe of net electrical power, a part of which is sold to the grid. The key characteristics of the two power plants are shown in Table 5.

Using steam from the primary steam cycle, as at Boundary Dam, reduces the coal-fired power plant electrical output, thereby increasing its cost of electricity generation. On the other hand, using a dedicated NGCC power plant to supply regeneration energy, as is the case at Petra Nova, increases the net power output of the station. However, this approach requires an additional capital investment for the NGCC facility, additional operating expenses for fuel and other variable costs, and additional CO_2 emissions from the combustion of natural gas.

In terms of the integration of the CCUS facility with the primary coal power plant, the different approaches used in Boundary Dam and Petra Nova have been assessed (Mantripragada and others, 2019). Detailed cost information for the two projects, including the economic implications of the two different methods of CCUS energy supply, are not in the public domain. To provide a consistent basis for comparison, the modelling approach adopted was therefore based on a generic 650 MWe new build coal power plant with a generic advanced amine (FG+) as the solvent. It should therefore be noted that the actual Boundary Dam and Petra Nova plant designs were retrofits of CCUS facilities to existing coal power plant, with both plants having different business models. The analysis below is thus an indication only for new power plant and does not directly relate to either Boundary Dam or Petra Nova power plants.

TABLE 5 COMPARISON OF BOUNDARY DAM AND PETRA NOVA CCUS DEMONSTRATION FACILITIES (MANTRIPRAGADA AND OTHERS, 2019)

Parameter	Boundary Dam	Petra Nova
Location	Saskatchewan, Canada	Texas, USA
New build/retrofit	Retrofit	Retrofit
Gross capacity, MW	160	240 (+ excess power from cogeneration plant)
Net capacity, MW	110	240
Coal type	Lignite	Subbituminous
Design capture rate, %	85–90	90
CO_2 use	EOR	EOR
$MtCO_2/y$	1.0	1.4–1.6
Solvent	Cansolv	KS-1
Regeneration energy	Steam from coal plant primary steam cycle	Natural gas cogeneration (70 MW using GE 7EA gas turbine, half the power for CCUS, with remainder sold to grid)
Project capital cost, US$ millions	1300–1500 (800 for CCUS)	1000

The analysis considered five configurations of a pulverised coal power plant equipped with post-combustion CO_2 capture technology using advanced amines:

- Configuration 0 – pulverised coal plant without CCUS (base case);
- Configuration 1 (based on the Boundary Dam configuration) – regeneration steam supplied from the primary steam cycle, with electricity provided from the power plant;
- Configuration 2 (based on the Petra Nova configuration) – regeneration steam and electricity supplied from an auxiliary NGCC power plant (with excess electricity production);
- Configuration 3a – regeneration steam supplied from a dedicated natural gas boiler, with electricity provided from the coal-fired power plant; and
- Configuration 3b – regeneration steam and electricity supplied from a cogeneration plant using a natural gas-fired boiler and a steam turbine-generator (with excess electricity production).

Full details of the analysis, together with the model assumptions, can be found in Mantripragada and others (2019) with the key outcomes below.

In terms of plant output and efficiency, the auxiliary gas turbine-based combined cycle configuration (Configuration 2) resulted in a higher net plant output and efficiency than the primary steam cycle configuration (Configuration 1), as shown in Figure 11a and Figure 11b. This is not surprising, due to the higher efficiency of the additional NGCC auxiliary power relative to the coal-based primary steam cycle and the higher electrical output.

In terms of CO_2 emissions, Configuration 1 has the lowest emissions and emissions rate, corresponding to a net CO_2 reduction of 86% compared to the reference case (Figure 11c). Due to the uncontrolled CO_2 emissions from the auxiliary gas-fired plants, the overall CO_2 capture rates for the remaining CCUS cases are much lower than for Configuration 1, with Configuration 2 having the lowest overall capture rate (65.6%). Thus, even though the cogeneration cases have higher thermal efficiencies than Configuration 1, they come at the expense of lower CO_2 reductions. Thus, although the Petra Nova-based model has a smaller loss in plant efficiency, the Boundary Dam-based model has a greater reduction in CO_2 emissions.

For the plant capital cost (*see* Figure 11d), on an absolute basis, the overall plant capital cost of Configuration 2 is about 7.5% greater than that of Configuration 1, and the cost of the CCUS system is about 30% greater. However, when normalised on the basis of net power output, the specific capital cost of Configuration 2 is about 40% lower than that of Configuration 1, indicating the strong impact of the additional net electricity generated in Configuration 2 from the auxiliary NGCC. Thus, because of the higher net power output of natural gas-based cogeneration plants, the specific capital cost of those plants is smaller than configurations where there is no cogeneration of electricity.

In terms of the levelised cost of electricity (LCOE), Configuration 2 has the lowest LCOE, primarily as a result of its higher net power output due to the auxiliary NGCC, as shown in Figure 11e. In addition, the cost results of Configuration 3a show that without cogeneration of electricity, using an auxiliary boiler for CCUS steam supply does not lead to any cost advantage over using steam from the primary steam cycle.

Looking at the cost of CO_2 captured and avoided (*see* Figure 11f), both of these costs are directly proportional to the difference in LCOE between the CCUS plant and the reference plant. The cost of CO_2 captured is inversely proportional to the amount of CO_2 captured and the cost of CO_2 avoided is inversely proportional to the difference in CO_2 emission rates between the reference plant and capture plant. The cost of capture is the minimum required selling price of CO_2 (EOR for example) and the cost of CO_2 avoided is the minimum required CO_2 tax or carbon price needed to make the plant with CCUS as economic as the reference plant. Whilst the total CO_2 captured is the highest for Configuration 1, the cost per tonne of CO_2 captured and CO_2 avoided are the lowest for Configuration 2 due to its lower LCOE.

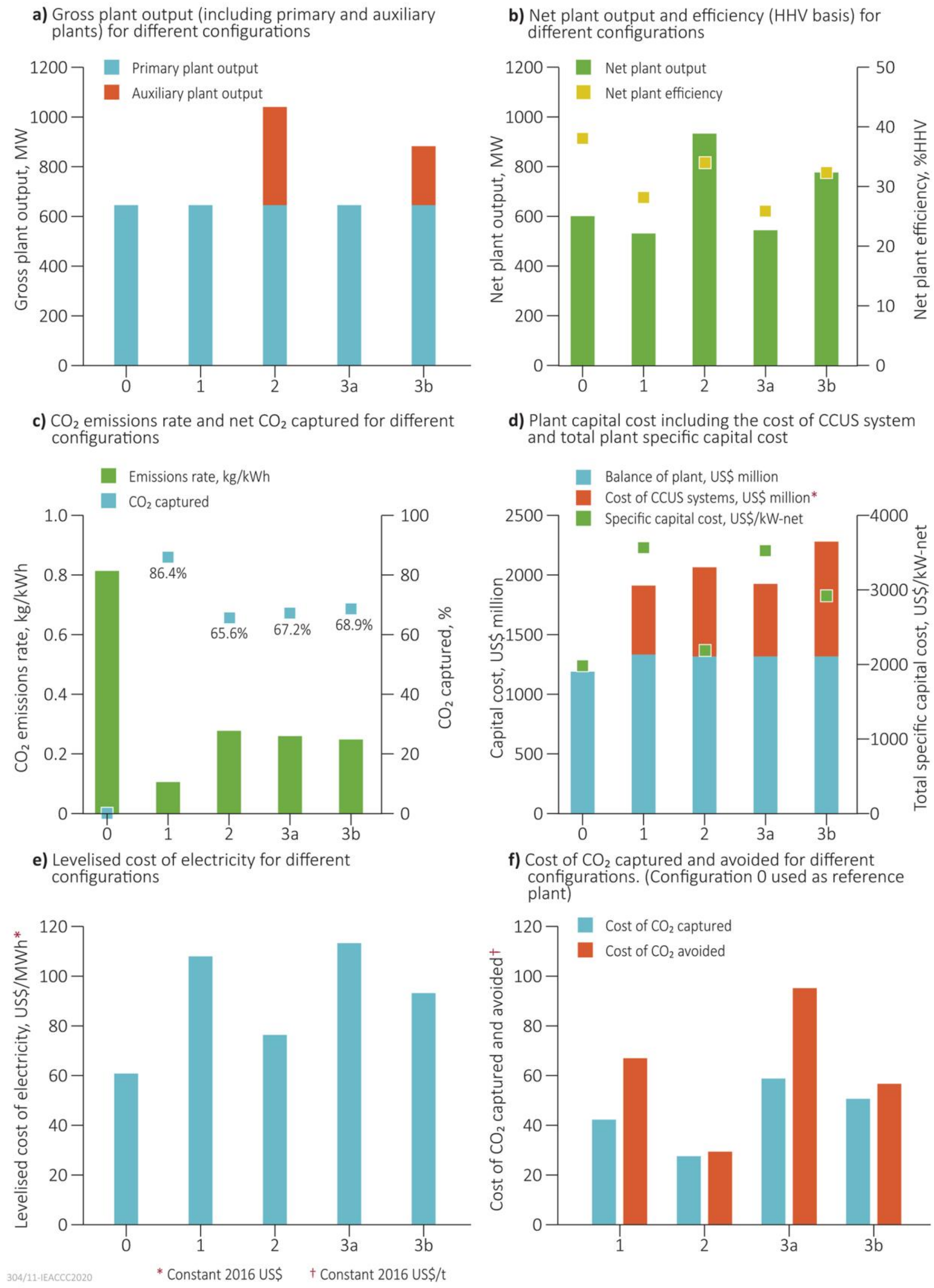


Figure 11 Key plant performance data for new build 650 MWe coal-fired plant models based on Boundary Dam and Petra Nova type configurations (Mantripragada and others, 2019)

In summary, this analysis indicates that using a GTCC cogeneration plant to supply CCUS regeneration steam and electricity has both thermal efficiency and cost benefits compared to the case where steam and electricity are supplied from the primary power plant steam cycle. In this regard, the Petra Nova model for solvent regeneration has several advantages over the Boundary Dam model for new build coal power plants. However, a key disadvantage of the auxiliary gas-fired configuration is the significantly lower overall CO_2 removal efficiency compared to the configuration using ‘coal only’ power plant (net capture rate of around 66% compared with 86% for the ‘coal only’ case). This is because there is no capture of CO_2 emissions from the combustion of natural gas for the Petra Nova type configuration with the overall CO_2 emission rate using the auxiliary gas plant options being over double that of the ‘coal only’ case based on the Boundary Dam model. There will of course be local factors that also play a significant part in determining the best approach, including cost and availability of natural gas and the existence of a market for the additional electricity from the NGCC.

A further analysis has been made based on the Shand project to assess the preferred supply of steam for solvent regeneration in a coal power plant CCUS retrofit in Canada (Jacobs and others, 2018). Details of the Shand project are presented in Section 5.1. This study showed that the steam cycle of a coal power plant can be re-engineered to provide steam for solvent regeneration at a significantly lower cost in terms of lost electrical output than can be achieved by an auxiliary gas-fired plant based on GE 7F gas turbine technology (*see* Figure 12). The gas-fired CHP arrangement performed best when it was dispatched at loads similar to the coal and capture plants, as the CHP arrangement significantly impaired the efficiency and flexibility of the gas turbine. The cost of steam for the coal plant, when used as a source of steam for solvent regeneration, increased as the load on the coal plant was reduced below 75%. However, there are expected to be limits on how much the steam to the low-pressure turbine can be throttled at reduced coal plant loads. This indicates the effect of local factors, such as the price of natural gas, compared with the study assumptions used in the modelling of Mantripragada and others (2019).

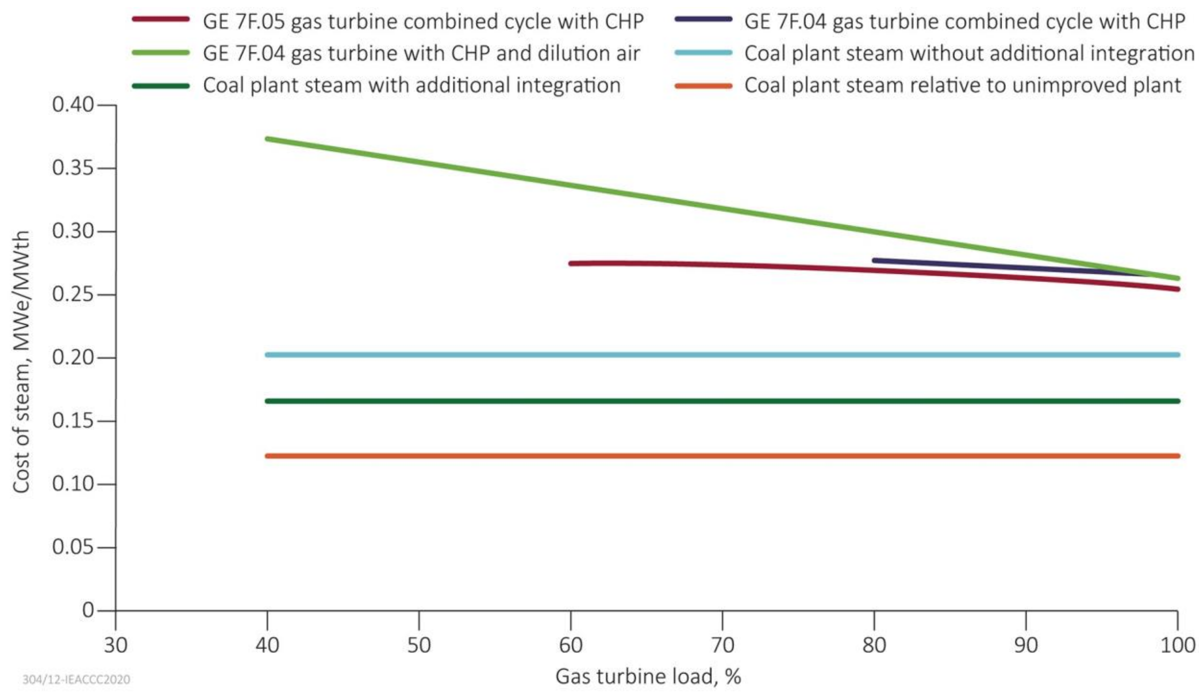


Figure 12 Comparison of cost of steam for CCUS facility amine regeneration with coal plant operating at full load (Jacobs and others, 2018)

A study has also been carried out by Bechtel (2018) for the retrofit of post-combustion capture to a lignite-fired power plant in Australia. The assessed retrofit options were:

- **Option A**: base case with stripper reboiler energy supplied by steam extracted from the steam turbine generator;
- **Option B**: alternative case with stripper reboiler energy supplied by steam from an auxiliary NGCC CHP plant with no carbon capture from the Heat Recovery Steam Generator (HRSG) exhaust gas; and
- **"Ultimate" Option B**: identical to option B but with carbon capture from the HRSG stack gas.

However, the results of this study in terms of capex and LCOE for the options were not available at the time of writing this report (April 2020).

4.4 SUMMARY

There are a total of 21 operational CCUS facilities globally, the majority relating to natural gas processing applications, with the potential to store around 39–40 MtCO_2/y. The leading power plant facilities are Boundary Dam in Canada and Petra Nova in the USA, both of which are coal-fired and have provided valuable design information for the further roll-out of CCUS. North America will remain an important region, but Asia, and in particular China, should become a key focus for the roll-out of commercial CCUS.

Availability of the power plant was an issue in the early CCUS demonstrations, but it has now reached acceptable levels. For example, the Boundary Dam CCUS facility has increased its availability to around 85% over the last 2 years, in line with the facility's design availability of 85%.

5 LESSONS LEARNED FROM CCUS DEMONSTRATION PROJECTS

Several studies have been carried out which aimed to identify the potential to reduce the costs of CCUS (CCUS Cost Challenge Task Force, 2018; Irlam, 2017). Generally they point to cost reduction through increased deployment at demonstration and subsequently commercial scale – so-called ‘learning by doing’. There is growing knowledge, based on the Boundary Dam, Petra Nova and the more recent pipeline of FEED studies, that provide the initial practical understanding to drive cost reduction and improve performance of next generation CCUS facilities. In addition, pilot and early TRL research projects are also underway to develop the potential for innovating existing technologies and developing new technologies which could bring step change cost reduction. This chapter focuses on the key learnings from the current coal-fired CCUS demonstration projects.

5.1 COST REDUCTION

Current carbon capture costs for coal-fired power plant with post-combustion CO_2 capture using amine based solvents are in the range of 105 US$/t$CO_2$ captured at Boundary Dam, to 65 US$/t$CO_2$ captured at Petra Nova (GCCSI, 2019a). The US DOE notes that carbon capture costs need to come down to around 30 US$/t$CO_2$ for CCUS to be commercially viable (GHGT, 2018). These costs will naturally come down in the future as CCUS technology becomes more commercialised through economies of scale. This effect has been assessed previously for other power generation technologies based on ‘learning rates’ (Zapantis and others, 2019). As shown in Figure 13, learning rates are typically in the range of 10–20%, meaning that for each doubling of plant capacity, the cost of the technology can be expected to fall by the learning rate, with coal-fired power plant having an average learning rate of 8%. Other studies have used the learning rate of 13% from flue gas desulphurisation plant cost reduction as a close analogy to the likely learning rate for CCUS technology.

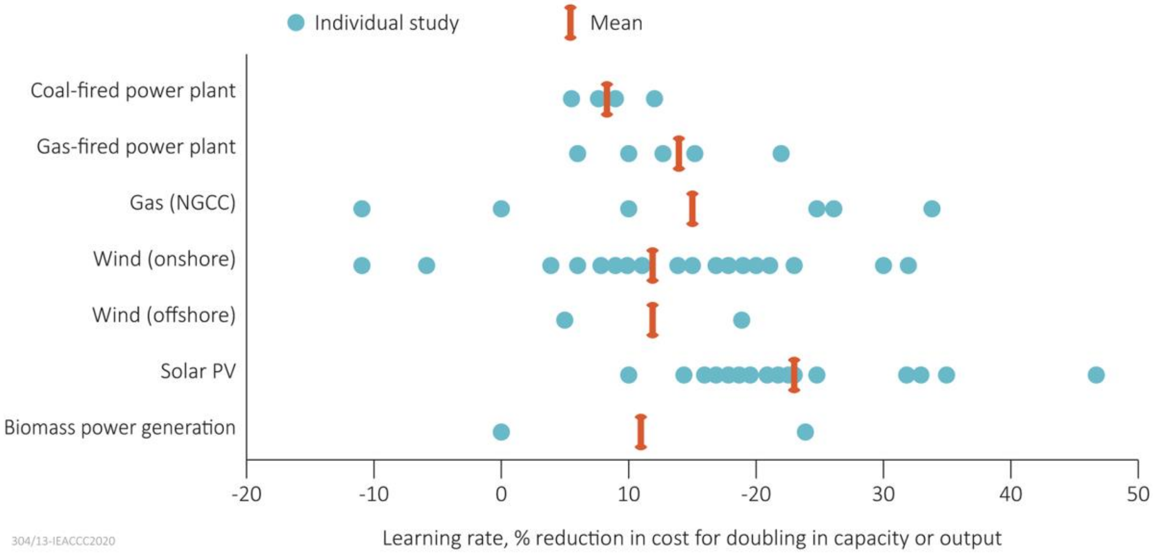


Figure 13 Typical learning rates for power generation technologies (Zapantis and others, 2019)

Based on these learning rates and assuming a target capacity of 170 GWe (*see* Section 2.1) of coal-fired power plant fitted with CCUS to achieve the IEA's SDS scenario (IEA, 2019a), a cost reduction for amine-based post-combustion CO_2 removal in the range of 50–70% could be achieved by 2050. If, however the future capacity of CCUS coal-fired power plant is lower (DNV-GL, 2019), with perhaps around 80 $MtCO_2$/y of captured from coal power plant, the cost reduction could be less at around 35-50%. Taking the current price of CCUS as the more recent Petra Nova price of 65 US$/$tCO_2$ captured, the price for future CCUS plant could therefore fall to as low as 19 US$/$tCO_2$, in the range of 19–43 US$/$tCO_2$ removed, depending on final capacity and the actual learning rate (*see* Table 6). It is therefore feasible that the cost of capture can come down to the required levels simply by capacity additions of current technology.

TABLE 6 POTENTIAL COST REDUCTION OF POST-PROCESS CAPTURE CCUS TECHNOLOGY BASED ON LEARNING CURVES (AUTHOR'S CALCULATIONS)

IEA SDS scenario capacity by 2050	Reduction in CCUS cost
8% Learning rate	52%
13% Learning rate	71%
DNV-GL capacity by 2050	Reduction in CCUS cost
8% Learning rate	34%
13% Learning rate	50%

It is interesting to compare the cost projected for the proposed Shand Power plant FEED study (Bruce and others, 2018; Int CCS KC, 2018) with the existing Boundary Dam project. The cost reduction projected for the single 300 MWe Shand coal power plant with 90% CO_2 capture is 57% relative to Boundary Dam, resulting in a cost of 45 US$/t CO_2 removed, with capital cost and variable operating and maintenance costs being the key areas for achieving this cost reduction (*see* Figure 14). This level of cost reduction is higher than that predicted by the above learning rate-based cost reduction, indicating that the learning rate is steeper at this relatively early stage of commercialising demonstration technologies. More details of how this cost reduction is proposed to be achieved are shown below.

The Shand FEED study fits into a cluster of more recent project studies at around the 43–45 US$/t CO_2 removed cost level, within a proposed timescale for commencement of plant operations by 2024-28, as shown in Figure 15. This figure also indicates the potential for a further reduction of cost by moving to advanced capture systems within a similar timescale, where costs below 35 US$/$tCO_2$ could be expected based on pilot plant tests.

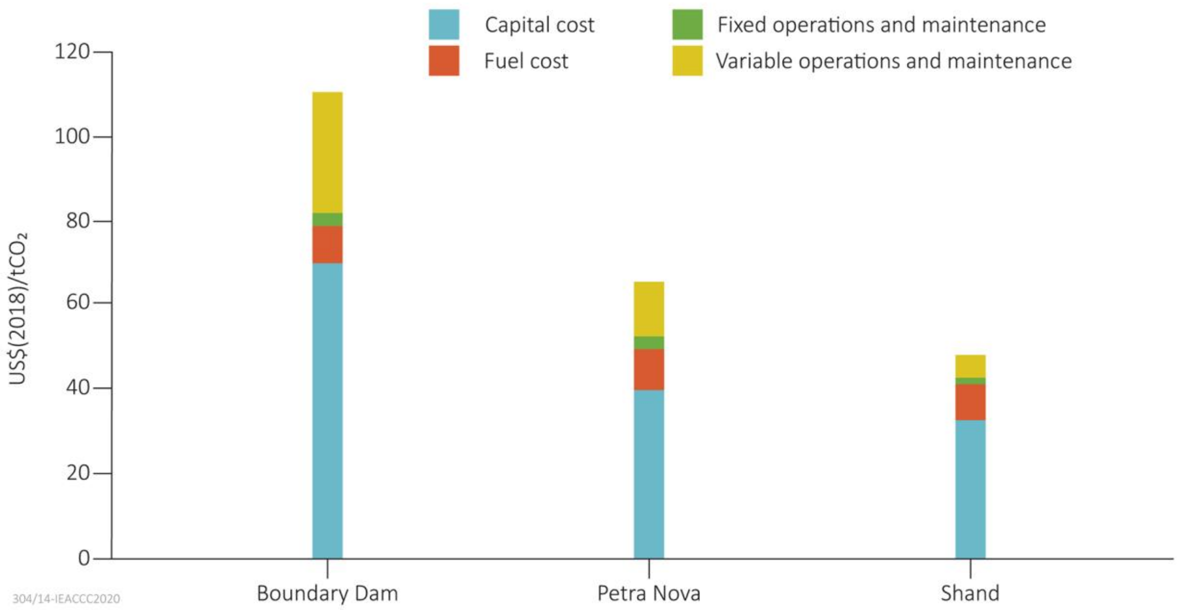
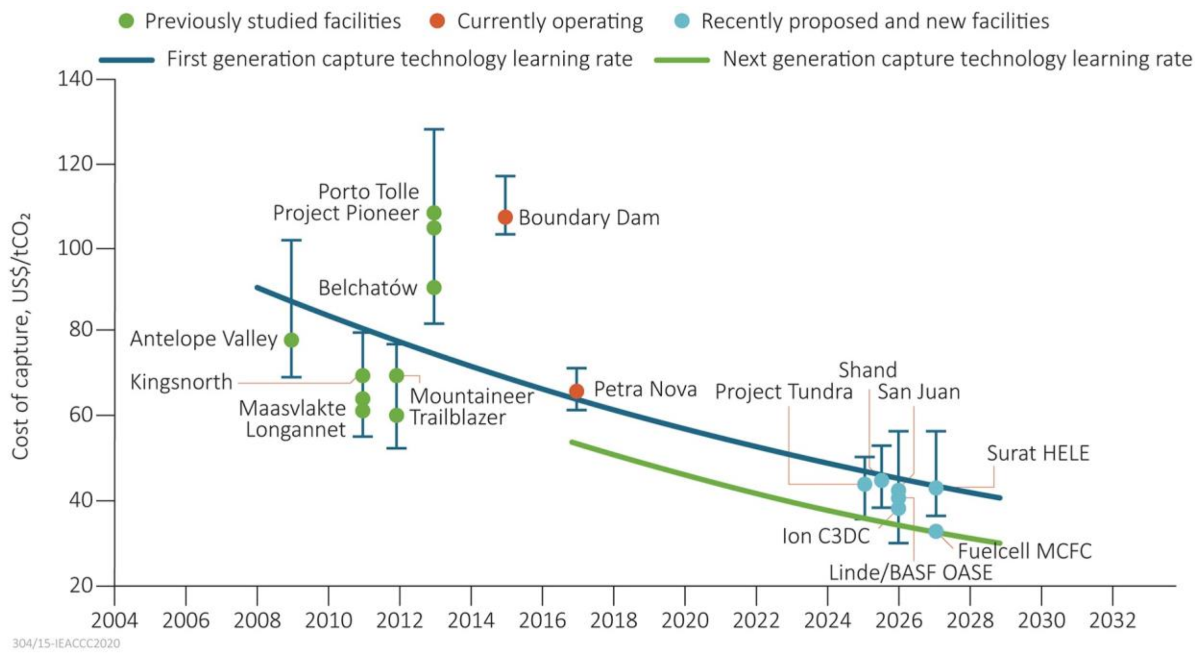


Figure 14 Comparison of cost reductions achieved and proposed relative to Boundary Dam (Zapantis and others, 2019)



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

Figure 15 Levelised cost of electricity for large-scale coal power generation plant with post-combustion carbon capture (Zapantis and others, 2019)

5.1.1 Cost reduction details for Shand FEED study

Shand Power Station is a single 300 MWe coal-fired plant unit plant in Saskatchewan, Canada which has been operational since 1992. At approximately twice the capacity of Boundary Dam, it is SaskPower's newest coal-fired power plant. The feasibility study (Int CCS KC, 2018) evaluated the business case for a post-combustion carbon capture retrofit, resulting in the addition of a 90% carbon capture facility with a nominal capacity of 2 MtCO_2/y. The study used MHI's KM CDR Process as used at Petra Nova, in order to provide a comparison with the Cansolv technology used in Boundary Dam. The assumptions and boundary conditions for the comparison are provided in Int CCS KC (2018).

Energy Cost of CO_2 capture - The energy cost of CO_2 captured was evaluated in terms of gross output increase due to modifications done concurrently with the CCUS retrofit, regeneration steam requirements and capture island auxiliary loads, as shown in Figure 16. This shows that the net change in energy consumption for the Shand facility is around 5% higher than Boundary Dam.

The key points from the analysis are that:

- Boundary Dam was near the end of its working life, requiring extensive modifications to be carried out in parallel with the CCUS facility retrofit. This enabled a greater increase in the existing power plant's gross output due to improved performance of equipment replaced;
- The Shand CCUS facility has a simpler flow sheet, resulting in a lower overall parasitic load of 22.9%, but at the expense of additional steam consumption for the regeneration system;
- The SO_2 removal system at Boundary Dam was based on amines, compared with a limestone based system for Shand, which reduced the auxiliary load requirements for Shand. However, the overall steam requirements are increased at Shand, despite the Boundary Dam amine regeneration system requiring additional steam. Although not shown in Figure 16 this increase in energy consumption is offset by the benefit of lower requirements for consumables due to the regenerable nature of amines.

Capital cost – due to system design constraints, both projects contain an SO_2 abatement system which is difficult to separate from the overall projects and so this element is included in the capital cost. In addition, in order to account for the lower level of heat integration for the Shand facility, primarily to reduce plant capital cost, the resulting loss in power generated was accounted for and converted to a cost value by requiring the project to 'purchase' this loss in power.

The capital cost for the Shand facility is projected to be 67% lower than for Boundary Dam on a US$/t$CO_2$ basis, as shown in Figure 17. Reduced capital cost for the CO_2 capture island, together with the lower level of power plant modification cost for the relatively more modern Shand power plant were the main contributing factors. This significant reduction in capital costs more than compensates for the lost energy penalty difference between the two projects.

Factors including scale, modularisation, simplifications and other lessons learned as a result of building and operating the Boundary Dam facility contributed directly to these reductions (*see* Section 5.2 onwards for further discussion).

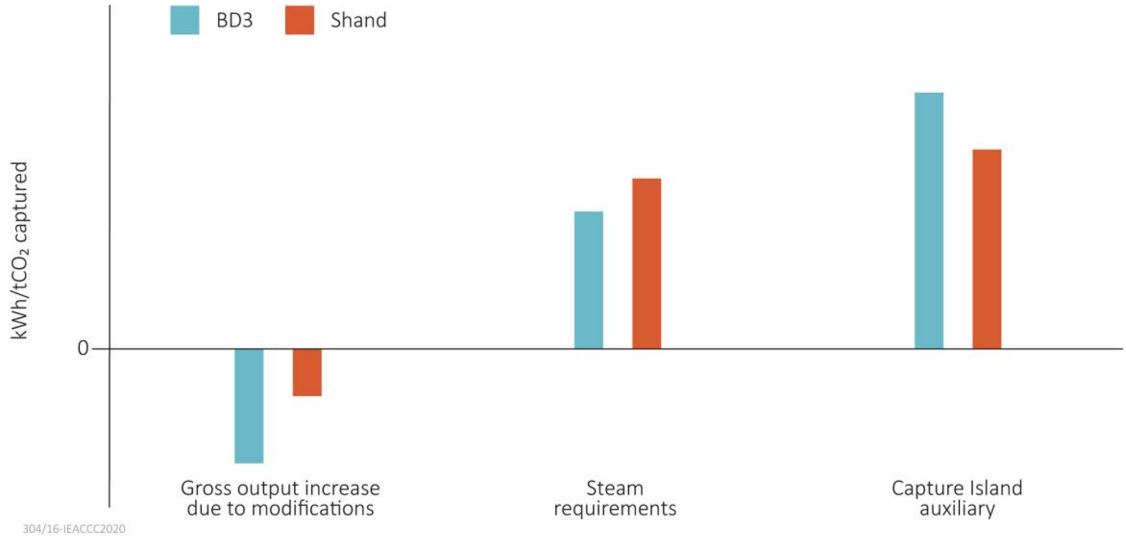


Figure 16 Comparison of CO_2 capture system energy penalty for Shand and Boundary Dam (Int CCS KC, 2018)

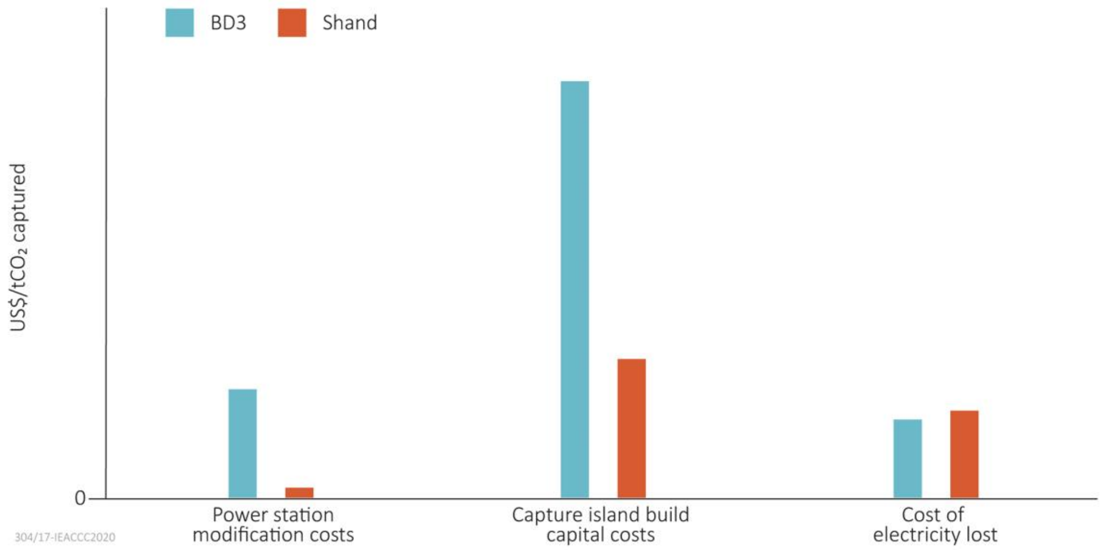


Figure 17 Comparison of CO_2 capture costs for Shand CCS facility compared with Boundary Dam (Int CCS KC, 2018)

Levelised cost of CO_2 capture – this included capture island capital costs, capture island operation, maintenance and administration (OM&A) costs, consumables costs, the cost of modifications to the power island and the cost of the power production penalty. Assuming a 30-year life span, the levelised cost of CO_2 capture was 45 US$/t, with the cost breakdown as shown in Figure 18. It should be noted that this cost is inclusive of costs related to SO_2 capture.

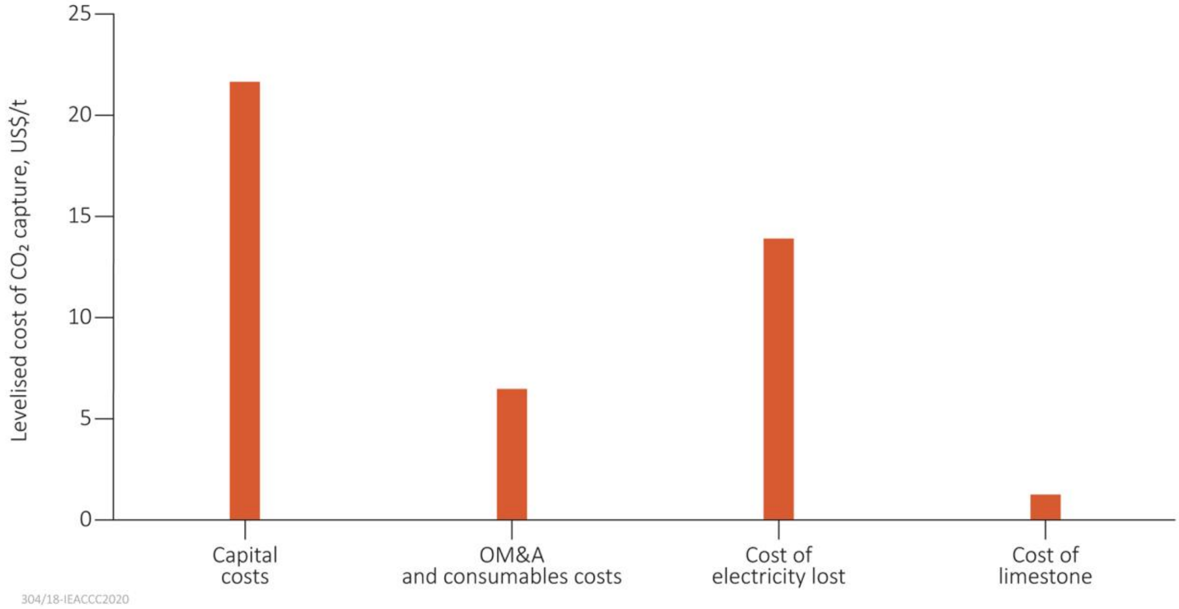


Figure 18 Breakdown of levelised cost of CO_2 capture for the Shand CCS facility (Int CCS KC, 2018)

5.1.2 Impact of global location on cost reduction potential

While the above analysis of CCUS costs is generally indicative of the position globally, there will of course be local factors giving rise to variations. This has been assessed by Irlam (2017) among others, with a comparison of first of a kind (FOAK) CCUS facility costs given in Table 7.

TABLE 7 COMPARISON OF FOAK PLANT CO_2 COST AVOIDED FOR DIFFERENT GLOBAL LOCATIONS (IRLAM, 2017)

Region/country	Supercritical pulverised coal, US$/t$CO_2$	IGCC, US$/t$CO_2$
Australasia		
Australia	104	135
Asia		
China	60	81
South Korea	93	120
Indonesia	74	106
Europe		
Germany	121	148
Poland	70	87
MEA		
Morocco	81	113
Mozambique	96	34
North and Central America		
USA	74	97
Canada	115	143
Mexico	81	114

Key observations are that:

- countries with lower labour costs (China, Mexico, Indonesia and Poland) and low energy costs (Saudi Arabia) have the lowest cost for implementing CCUS;
- while China is a relatively cheap location, it has experienced rising costs of production because of increasing labour costs and the addition of an import tax;
- the cost of CO_2 storage contributes relatively small amounts to overall project costs. For onshore storage, the combined cost of transport and storage is estimated to be between 7–12 US$/t$CO_2$. Offshore transport and storage costs are estimated to be between 16–37 US$/t$CO_2$; and
- revenue from the sale of captured CO_2 for EOR has been the principal means of bringing CCUS facilities to market for those regions which have a local oil and gas production sector.

The result is that the cheapest locations for coal-fired generation with CCUS in terms of US$/t$CO_2$ are the USA, Canada, Mexico and China, which is reflected in the databases of projects (GCCSI, 2019a; NETL, 2018), as summarised earlier in Table 2.

A further study (Ferrari and others, 2019) considered location specific economic factors to assess global locations for CCUS relative to a base case plant costing in the Netherlands. Considering total plant costs, China had the greatest cost reduction at around 35% less than the related case in the Netherlands location, due to the significant savings in material and construction labour costs. Indonesia and Eastern Europe were next lowest with around a 20% cost reduction (*see* Figure 19). In terms of the cost of CO_2 avoided, the impact of plant location is shown in Figure 20. As this cost correlates primarily with plant capital cost, it is not surprising that the lowest cost of CO_2 avoided is in China with a value of around 50 €/tCO_2 (about 55 US$/t$CO_2$) avoided, with the highest costs at 70-75 €/t CO_2 (about 80–85 US$/t CO_2) avoided in South Africa and Australia.

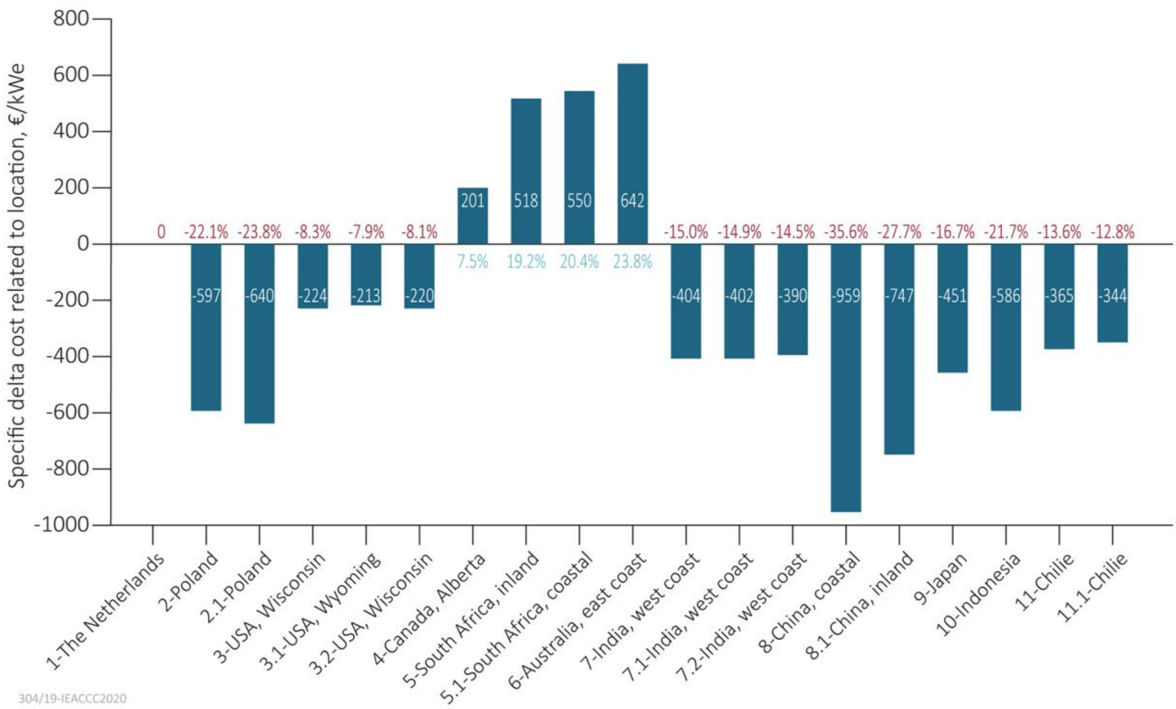


Figure 19 Supercritical coal power plant with post-CO_2 capture: specific total plant cost difference due to plant location compared to reference Netherlands base case (Ferrari and others, 2019)

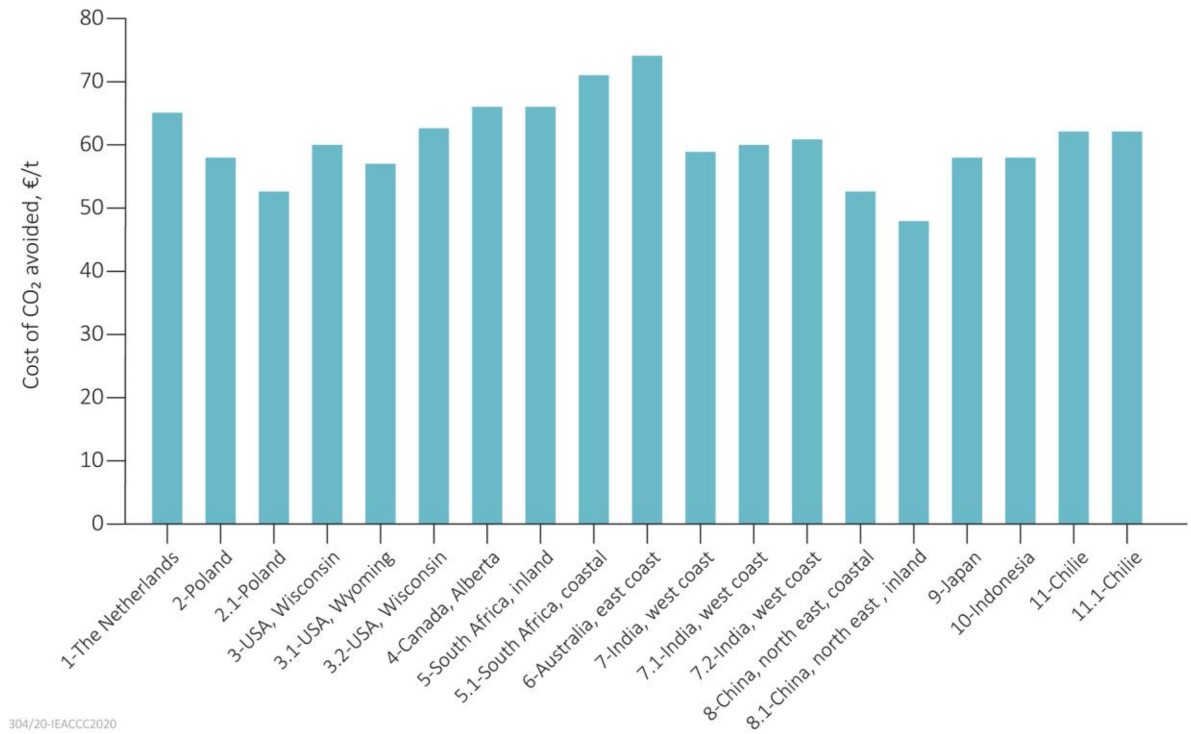


Figure 20 Cost of CO_2 avoided for supercritical coal power plant with post-combustion capture (Ferrari, and others 2019)

5.2 SCALING-UP THE CCUS PLANT

As a general rule, power plants become cheaper at larger scale in terms of US$/kWe output, due to economies of scale. The Boundary Dam 3 power plant is 110 MW net (160 MW gross) power output, and the Shand FEED study is aimed at the retrofit of a 300 MW coal power plant. The size of the CCUS facility is approximately doubled in size from 1 $MtCO_2$/y captured to 2 $MtCO_2$/y captured. The Shand feasibility study demonstrated that 57% cost reduction could be achieved on a per unit of CO_2 capture basis, due in part to the larger scale of the power unit (Int CCS KC, 2018; CIAB, 2019).

The size of these coal boilers in Canada is relatively small compared with modern coal-fired power plant globally, where boiler sizes are typically 660 MWe to over 1 GWe. This indicates that there is significant potential to reduce costs further through economies of scale. There are a number of IEACCC studies covering the impact of coal power plant efficiency, including Barnes (2018, 2019a).

5.3 SITE LAYOUT AND MODULARISATION

The layout of the CCUS facility is a key design feature to reduce plant footprint and therefore minimise the CCUS facility capital cost. The location of the capture facility in close proximity to the power island reduces the length of interconnecting pipework which leads to reduced cost of materials, reduced complexity of facility integration and therefore increased operating efficiency. The layout of the Shand site was fortunate in this regard as it was initially designed to host a second power unit which was not built, resulting in relatively low site congestion. It is therefore feasible to site the energy intensive CCUS unit operations close to the power island, with the CO_2 absorber tower located next to the boiler house, the CO_2 desorber alongside the boiler/turbine house and the CO_2 compressor beside the power generator. This alignment minimised the length of interconnections for flue gas ducting, steam piping, and electrical connections, which reduced material costs significantly. Additionally, sharing of building infrastructure between the original power plant and the CCUS facility reduced personnel access costs. Conversely, Boundary Dam and Petra Nova did not benefit from this availability of space close to the power island, resulting in increased costs and fewer opportunities for performance enhancement with the CCUS facility.

Modular construction for major infrastructure projects is being used successfully to drive down costs in global power plant construction projects, as discussed in the report published by the IEACCC (Mills, 2019). While such modularisation is not possible in all cases, the assembly of structural steel, equipment, piping, electrical and instrumentation offsite has been shown to increase productivity, reduce travel costs and result in shorter on-site construction time. This approach would also have the advantage of allowing more sub-assemblies to be built in lower cost regions and reduce on-site construction times, both of which should contribute to reducing overall costs.

5.4 INCREASING CAPTURE CAPACITY

CCUS based on post-combustion CO_2 capture typically aims at a 90% capture level. In the longer term however, as near-zero emissions power plants will be needed to contribute to a net zero CO_2 future, higher capture efficiencies will be required. This is evident in the projections by the IEA (2017), where coal power plant with CCUS starts to fall away after 2045 due to their residual CO_2 emissions (*see* Section 2.1 and specifically Figure 6).

A study (Feron and others, 2019) has shown that from a technical perspective, there is no limiting factor to the increase of capture rates from the usual 90% to higher levels. A fossil fuel power station could be made effectively CO_2 neutral by capturing 99.7% of the CO_2, utilising intercooling in the CO_2 absorption tower for example. This however increases the capital cost of the CCUS facility due to the requirement for larger sized equipment (absorber/desorber columns, heat exchangers and CO_2 compressor), as well as increased energy consumption. For an ultrasupercritical coal-fired power plant the efficiency (based on LHV) is reduced from 44.4% to 34.5% for 90% capture, and to 33.0% to move to 99.7% CO_2 capture, representing an additional drop of 1.5 percentage points in efficiency. The cost per tonne of CO_2 avoided increases from 55.0 €/tCO_2 at 90% capture level to 56.9 €/tCO_2 at 99.7% capture level, which is an increase of 3.5%. The avoided costs for 99.7% CO_2 capture level determined at fuel costs ranging between 1 and 4 €/GJ vary between 49–61 €/tCO_2.

This compares with the alternative approach of achieving net zero in a coal-fired power plant of cofiring 90% coal with 10% biomass, together with utilising 90% CCUS. Here the cost of CO_2 avoided will be between 53–59 €/tCO_2 for the range of fuel costs, indicating that the biomass cofiring option is potentially more expensive at fossil fuel costs below 2 €/GJ (Feron and others, 2019).

5.5 INCREASING EFFICIENCY OF THE PRIMARY POWER PLANT

Older coal-fired power plants have steam cycles with lower steam cycle pressure and temperature, often at subcritical conditions, and CO_2 emissions typically in excess of 1200 tCO_2/GWh. The Shand power station is a subcritical, lignite-fired unit with an emission intensity of approximately 1100 tCO_2/GWh. A modern 45–46% LHV, ultrasupercritical coal power plant, with steam temperature greater than 593°C and pressure greater than 24 MPa, can have a much lower emission rate of below 750 tCO_2/GWh. There is therefore around a one-third reduction in emissions intensity between the older and more modern coal power plants, which has a direct impact on the size of the CCUS plant, reducing parasitic power losses and capital cost (Barnes, 2018, 2019; Zhu, 2020).

5.6 OPERATING COST REDUCTION

The inclusion of a CCUS facility on a coal-fired power plant necessarily reduces the plant's overall efficiency and increases its operating costs. This is because the CCUS facility requires energy to operate the capture and compression systems which reduces the net energy output of the power plant, or as in the case of Petra Nova incurs additional operating costs for the auxiliary NGCC power island, together with increased operating costs due to the CCUS use of solvents, chemical reagents, catalysts and disposal of waste products.

Based on the experience at Boundary Dam and Petra Nova, the largest potential for operating cost reductions is in the areas of reduced amine degradation, key component redundancy/duplication and system integration. Early challenges faced by these facilities have highlighted the areas where the largest gains could be made to reduce operating costs.

5.6.1 Amine degradation

Amine molecules tend to break down or degrade during use leading to a reduction in capture efficiency. This requires periodic removal and replacement of the solvent, which has an impact on the CCUS system operating cost and presents an operational risk for amine-based post-combustion capture systems. Amine degradation risk mitigation through extensive piloting is carried out as part of some CCUS facility designs (CIAB, 2019). This can help to establish the CCUS facility business case, but also increases the cost of development and the timeframe for CCUS deployment.

Technology providers have focused on the reduction of the impact of amine degradation and the associated costs for managing amine quality. For example, MHI have developed an improved amine-based KS-21 solvent system which reduces the capital cost of the amine capture system by 30% relative to the current KS-1 solvent-based system as used at Petra Nova (Kamijo, 2019). This is achieved primarily through a 40% reduction in the size of the direct contact cooler, 30% reduction in the size of the absorber absorption section and 40% reduction in the size of absorber water wash section. Additional cost reduction is achieved through modularisation, reduced design margins and optimised plant layout as noted already in this chapter. In terms of the solvent itself, a significant reduction in amine thermal degradation is targeted which allows higher system stripping temperature and pressure to be used, together with reduced compression work (*see* Table 8).

TABLE 8 COMPARISON OF MHI KS-1 AND KS-21 SOLVENTS (KAMIJO, 2019)

	KS1	KS-21
Volatility	1	0.5–0.6
Thermal degradation rate	1	0.3–0.5
Oxidation rate	1	0.7
Heat of absorption	1	0.85

5.6.2 Component redundancy for reduced maintenance costs

An increased understanding of the impact of maintenance on operating costs for the latest CCUS facilities (*see* Section 4.1) has been developed based on the Boundary Dam and Petra Nova systems, along with effective strategies to optimise operating equipment.

To reduce the likelihood of unscheduled or emergency maintenance, which typically has a major impact on operating cost, the duplication of key system units to provide redundancy can be included in the system design. This clearly has an impact on capital cost but can be offset by the increase in availability of the CCUS facility. The approach enables continued operation of the CCUS facility using the duplicate equipment whilst carrying out in-situ maintenance of the faulty equipment. Ideally existing plant staff perform this work during normal working hours, resulting in reduced CCUS facility operating costs.

5.6.3 CCUS facility bypass

For the Shand FEED study, the ability of the power plant to continue to produce electrical power in the event that the CCUS facility is shut down, as is the case with Boundary Dam, is a key risk mitigation strategy. Referred to as 'dual mode' operation, it allows steam consumption to be varied somewhat independently of CCUS facility demand, with diverter dampers allowing flue gas to be sent to either the original stack or the capture facility or a combination of the two. While the dual modes provide reliability for the power plant, it is the ability to partially bypass the capture plant that is a key to flexibility. This allows design margins in the CCUS facility to be lower, reducing cost.

5.6.4 System integration

One of the key challenges for a fully integrated, post-combustion capture system, as is the case in Boundary Dam, is to reduce the impact of the CCUS facility energy requirements on the host power facility. An analysis of steam cycle options for integration with the CO_2 capture plant has been carried out in an IEACCC report by Henderson (2015).

Sourcing energy from the power plant imposes an additional parasitic load that reduces net power output from the power plant. A considerable amount of research and technological development has minimised the energy requirements of the CO_2 capture process, leading to commercial proprietary solvents, such as those used at Boundary Dam and Petra Nova, that offer performance advantages and reduce energy needs by as much as 30% compared to benchmark amines.

In terms of steam extraction for the Shand FEED study, preliminary analysis has indicated that the regeneration energy should be able to be sourced from the steam turbine relatively efficiently with few changes to the feed-heating plant and bolt-on modifications to the steam turbine. In addition, it was determined that the modifications would still allow the unit to run at full load, even when steam was not being extracted for the CCUS facility (Jacobs and others, 2018).

5.7 OPTIMISING THE CCUS OPERATING ENVELOPE

Based on experience from Boundary Dam, for a nominally designed full load capture capacity of 90%, this capture rate can be exceeded when operating at part load conditions, with over 96% capture being possible at 75% power plant load (Int CCS KC, 2018). This would mean that coal-fired power plant with CCUS could operate flexibly around renewable power generation with minimal impact on the overall near-zero emissions target (*see* Figure 21). This could be an interesting selling point for the role of coal power plant within an overall integrated energy system to deliver minimised emissions.

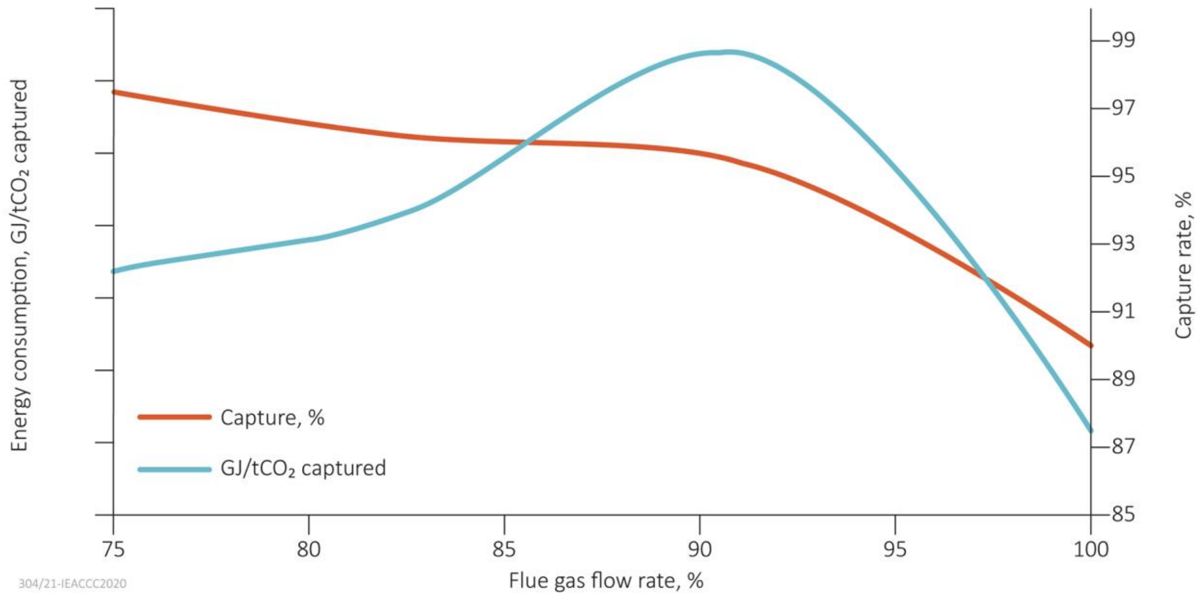


Figure 21 Effect of part load operation on CO_2 capture rate (Jacobs, 2019)

In addition, a post-combustion CCUS facility can increase the heat rejection load of a coal-fired power plant by around 50%. Since the availability of cooling water is limited in many locations globally and is set to become an increasingly important design constraint, it is likely to be a limiting factor in new build CCUS and retrofit to existing power plant sites (Carpenter, 2018; Barnes, 2019b). This was the case for the Shand FEED study, compounded by the significant ambient annual temperature range of -40°C to +40°C. In this case, a de-rating of the CCUS facility was viewed as being acceptable at high ambient temperatures, with the impact being a slightly lower CO_2 capture giving an increased power output. Conversely at low ambient temperature the level of CO_2 capture is increased. For the Shand study, the heat rejection system was designed for the 85th percentile, which provided cost reduction at the expense of reduced margins. The only new water used in the system is the water condensed out from the flue gas. The use of a hybrid cooling system with dry coolers and wet surface air coolers allows the amount of water evaporated to be controlled by biasing heat rejection duty between the two coolers, which results in an air cooler system with high approaches and an evaporative system which provides the lower approach final cooling of the circuit. This type of cooling system has the potential to be a reasonable first approach at any coal-fired power plant (Int CCS KC, 2018).

5.8 DEVELOPMENT OF A CCUS SUPPLY CHAIN

Developed supply chains increase competition, spur innovation and reduce technology costs, which in turn has a positive impact on capital cost. Development of a CCUS supply chain would of course depend on a sustainable market for CCUS in which suppliers have confidence. Characteristics of a well-developed supply chain include:

- supply of all CCUS associated equipment within reasonable timeframes to meet demand;
- suitable competition between equipment suppliers that would drive efficiency, innovation and drive component cost reduction; and
- standardisation and significant volumes of supplier orders that would enable expansion by manufacturers toward efficient scales of production.

5.9 SUMMARY

The cost of CCUS, which is probably the single most important lever for wide-scale roll-out of the technology, has reduced significantly, with a current cost of capture of around 65 US$/t$CO_2$. Further cost reductions can be expected through ‘learning by doing’ where perhaps a 50–70% cut could be achieved as the technology is rolled out commercially. Recent project studies including the Shand FEED study predict CO_2 capture costs of around 43–45 US$/t$CO_2$ removed, within a proposed timescale for commencement of plant operations by 2024-28.

CCUS capture levels will need to increase from the current 85–90% to closer to 100% to allow the power plants to continue to operate in a net zero emission future as any residual CO_2 emissions from CCUS facilities will not be compliant without being offset from negative CO_2 emissions elsewhere. Where auxiliary plants are used to provide steam and energy for the CCUS facility, they will also need to include CCUS to achieve very high capture levels overall.

6 OPPORTUNITIES FOR CCUS ROLL-OUT

Having reviewed the need for CCUS as part of an integrated approach to achieve net zero CO_2 emissions targets by 2050 (Chapter 2) and assessed the potential for cost reduction based on the learnings from the CCUS demonstration projects (Chapter 5), this section of the report assesses the opportunities to achieving a wider commercial roll-out of CCUS on a global scale. A detailed analysis of the barriers to CCUS has been carried out previously by the IEACCC (Lockwood, 2018a).

6.1 CURRENT DRIVERS SUPPORTING CCUS

There are currently 21 CCUS demonstration projects in operation globally storing around 39-40 $MtCO_2$/y, with a further three in construction and additional projects in the pipeline (*see* Table 2 for details). Whilst a comprehensive framework to support the wide-scale roll-out of CCUS remains to be established, supportive policy measures and project conditions are in place in a number of regions which have supported the establishment of the current and proposed CCUS demonstrations, as shown in Figure 22 (Havercroft, 2018; Havercroft and Consoli, 2018).

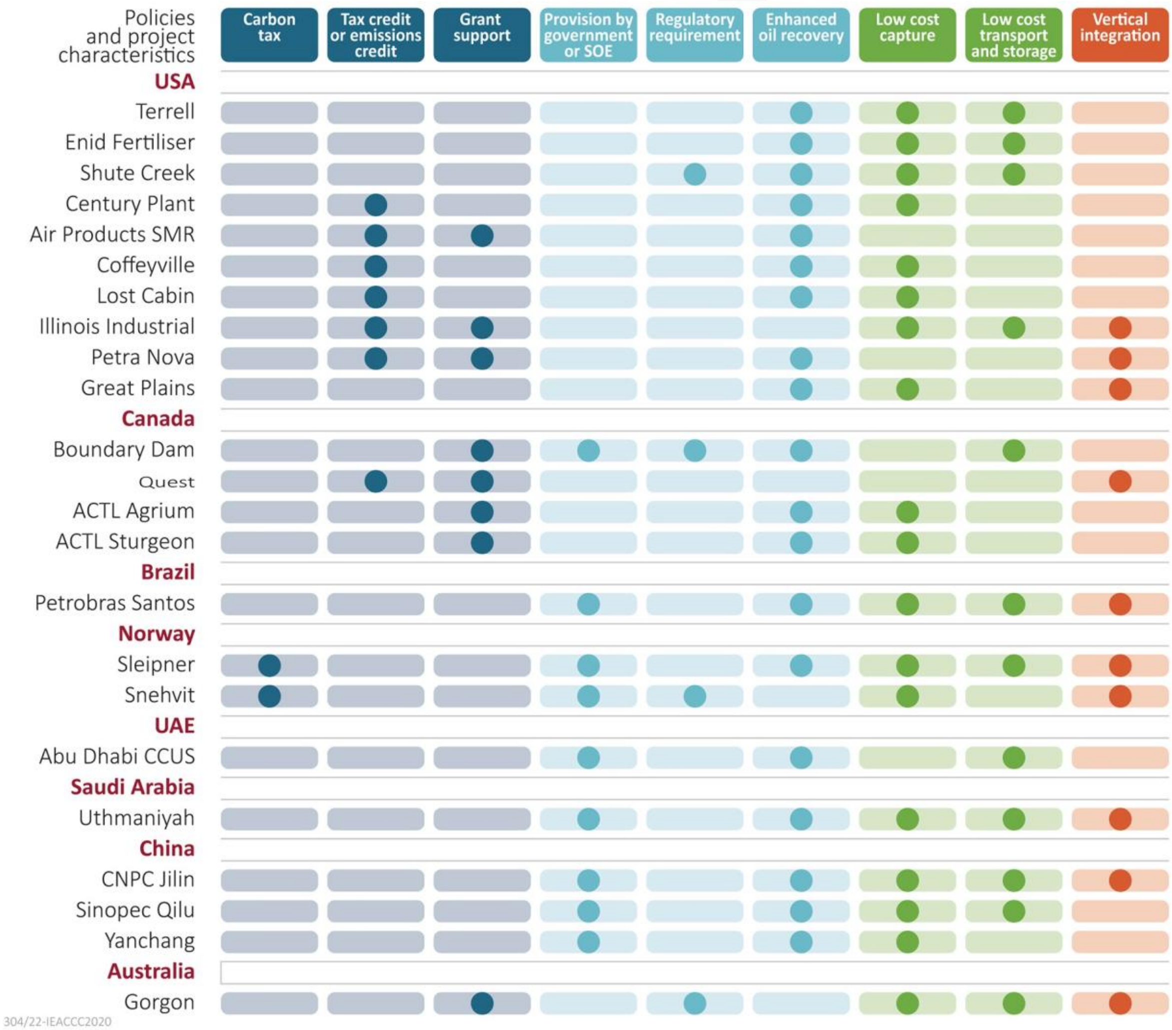


Figure 22 Policies and characteristics supporting CCUS demonstration projects (GCCSI, 2019a)

For the early CCUS demonstration plants, a proportion of the increased operating costs may be absorbed by the project developer as part of a wider business strategy for example, to improve their environmental image, ease government approval for a particular project, or help promote their own CCUS technology (Lockwood, 2018a). This type of longer-term investment strategy has played a role in the early development of CCUS, particularly in projects led by oil and gas sector companies such as the In Salah project (BP, Sonatrach, and Statoil), Shell's Quest project, and Chevron's Gorgon project (Herzog, 2016). A further example of this longer-term vision of technology providers and key stakeholders is the OGCI. With thirteen oil and gas company members (as of 2019), comprising BP, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Pemex, Petrobras, Repsol, Saudi Aramco, Shell and Total, the organisation invests in innovative, commercially viable and scalable technologies and solutions. OGCI Climate Investments for example is a US$1 billion-plus-fund set up by the OGCI member companies to lower the carbon footprint of the energy and industrial sectors (OGCI, 2019).

The primary financial mechanism supporting CCUS has been through the value placed on the captured CO_2 for EOR. As noted in Table 2, 14 out of the 19 CCUS demonstration projects, representing close to 75% of them are supported by revenues derived from sale of the CO_2 for EOR. With revenues in the range of 10–35 US$/t$CO_2$, EOR is generally insufficient to cover the costs of CCUS alone, certainly for coal-based power plant applications (Jenkins, 2015). At the higher end of the range, it can however cover the costs of capturing and transporting CO_2 in sectors where the cost of capturing CO_2 is relatively low, such as natural gas processing, fertiliser and bioethanol production (Zapantis and others (2019).

6.1.1 Tax credits

Tax credits are a policy instrument which reduce the tax liability of a tax-payer for fulfilling a defined criteria, in this case storing CO_2. A key feature of tax credits is that they are performance based in that they are only awarded when CO_2 is captured and stored in conformance with federal requirements. The credits can be used to reduce a company's tax liability or, if they have no tax liability, be transferred to the company that disposes of the CO_2 or traded on the tax equity. Tax credits have the benefit of being well established in the context of climate change mitigation in the USA, having been used to drive significant investment in renewables over the past two decades.

Tax credits in the USA have supplemented the revenues from EOR projects and have also provided an incentive for the geological storage of CO_2. Known as 45Q tax credits, these seek to link directly the financial compensation to the amount of CO_2 stored. This has been recognised as an enabler of the six large-scale facilities in the USA that have come on stream since 2011, including Petra Nova, Century Plant, Air Products SMR, Coffeyville, Lost Cabin and Illinois Industrial (*see* Table 2 for project details).

Section 45Q underwent a major reform in 2018 so that now the tax credit increases linearly each year to a maximum of 50 US$/t$CO_2$ for saline aquifer-based geological storage or 35 US$/t$CO_2$ for EOR by

2026, tracking inflation thereafter, as shown in Table 9 (Clean Air Task Force, 2017). Under the current arrangements, 45Q provides tax credits worth 20 US$/t$CO_2$ for CO_2 used for EOR and 32 US$/t$CO_2$ for CO_2 stored through dedicated geological storage. The reform removed a cap on how much money could be paid out under the system, which was equivalent to 75 MtCO_2 captured in total for the tax credit scheme. It also retains the 45Q eligibility threshold for a minimum annual CO_2 volume per project of 500,000 t for power plants, but lowers it for industrial sources and DAC to 100,000 t. The legislation makes the tax credit available for non-EOR utilisation and geological storage of CO_2 with the minimum eligibility threshold set at 25,000 tCO_2/y. To be eligible, the CCUS projects must commence construction before 2024 and can receive the credits for up to 12 years.

An update on the status of the 45Q tax credit indicates that the 45Q has already led to a series of project announcements in the USA (Beck, 2020). Of the eight projects added to the GCCSI's CO2RE database (GCCSI, 2019b) in late 2019, four cited the 45Q tax credit as a key driver. In terms of the tax credit itself, the update notes that stakeholders have proposed adjustments and changes to the credit. This includes a delay in the commencement of the construction deadline by at least two years, to account for the two years waiting for guidance on the process of credit implementation.

This significant new incentive could help spur a new wave of CCS investment of coal and natural gas power plants in the USA, capturing a potential 49 MtCO_2/y by 2030 (Nagabhushan and Thompson, 2019). Importantly, these power sector carbon reductions due to 45Q induced deployment of CCUS are additive to those achieved through renewable sources of electricity generation. This means, that fossil fuel power stations fitted with CCUS are replacing unabated fossil fuel-fired power rather than replacing existing renewable energy capacity.

TABLE 9 45Q TAX CREDIT ESCALATOR (NAGABHUSHAN AND THOMPSON, 2019)

Calendar year	EOR, $/t$CO_2$	Saline geological storage, US$/t$CO_2$
2017	12.83	22.66
2018	15.29	25.70
2019	17.76	28.74
2020	20.22	31.77
2021	22.68	34.81
2022	25.15	37.85
2023	27.61	40.89
2024	30.07	43.92
2025	32.54	46.96
2026	35.00	50.00

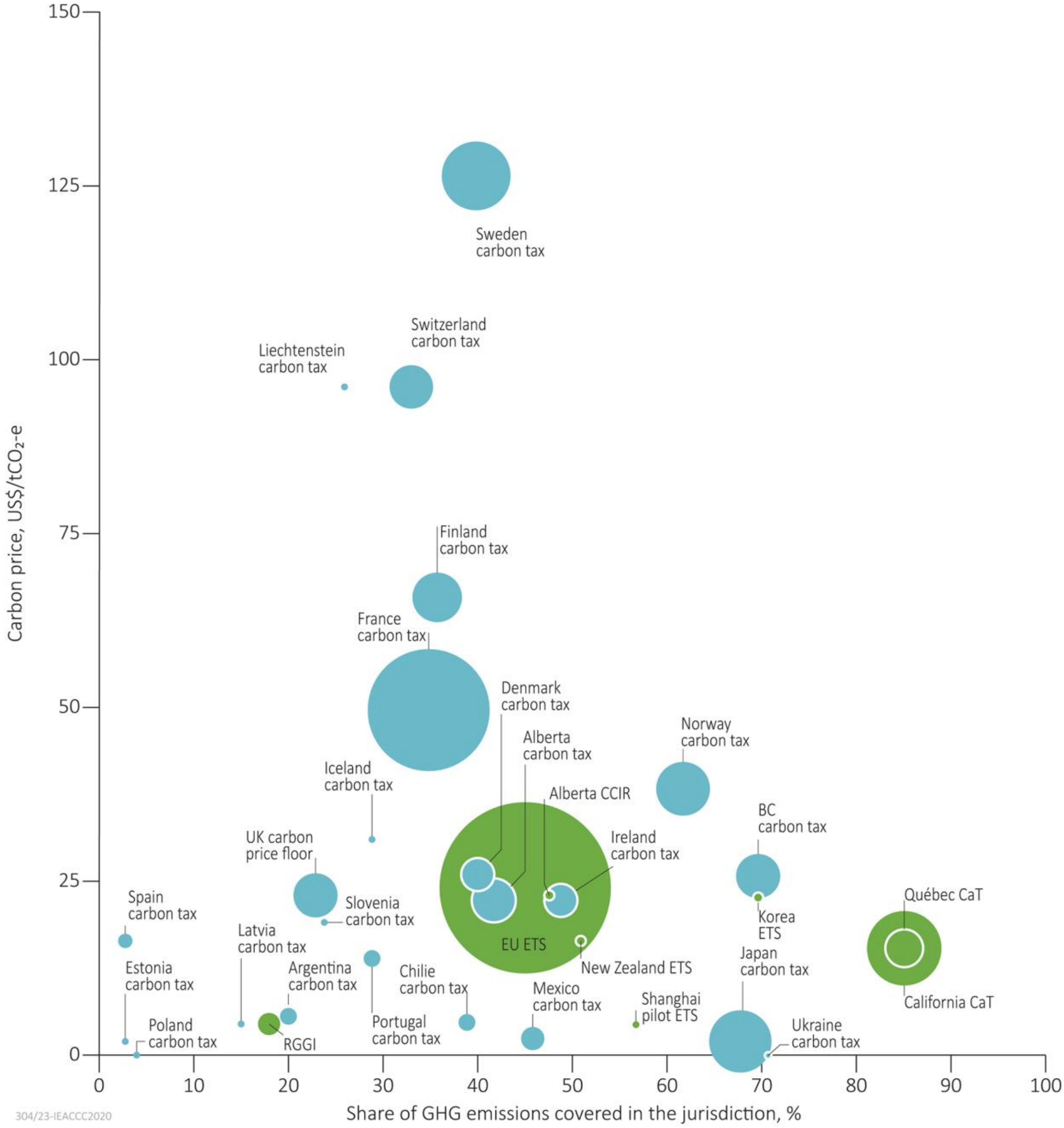
Similar tax credit based incentives are being considered in other countries such as China. Here, studies show that CCUS costs are still high for coal-fired power plants in China, and 45Q tax credit type provisions can effectively improve the investment benefits of CCUS projects (Fan and others, 2018, 2019). However, from the perspective of large-scale CCUS deployment, the incentive effect of the tax credit depends on the application. For a full chain CCUS system including CO_2 capture and geological storage, the 45Q tax credit provisions would need to be combined with CO_2 trading to enable a coal-fired power plant to capture 90% CO_2 emissions continuously over a typical 40-year coal plant life span. This is because the 45Q tax credit income time-frame is assumed to be 12 years in the study, as is the case in the USA. Where the captured CO_2 could be exploited for EOR, the coal plant could maintain an income stream beyond the initial 12 year tax credit timeframe. As a result, the Chinese government can learn from the 45Q mechanism, but at the same it would need to encourage coal power generators to explore further CO_2 utilisation approaches such as EOR to increase the economic value of CO_2.

6.1.2 Carbon pricing

According to the World Bank (2019), fifty-seven carbon pricing initiatives have been implemented, or are scheduled for implementation. They consist of 28 emissions trading schemes (ETS), spread across national and subnational jurisdictions and 29 carbon taxes, primarily implemented on a national level. These carbon pricing initiatives account for around 11 $GtCO_2$ equivalent, or about 20% of GHG emissions. More positive carbon price signals would help to drive the growth in CCUS necessary to achieve the required reductions in global CO_2 emissions. Whether the carbon price is effectively valued through carbon emitted or emissions trading schemes, the value needs to be around 40-80 US$/$tCO_2$ by 2020, increasing to 50–100 US$/$tCO_2$ by 2030 (World Bank, 2019). Currently, less than 5% of global CO_2 emissions have a carbon pricing regime which is consistent with this. According to the OECD (2019), little progress has been made in extending tax-based carbon price signals. Since 2015, average effective carbon tax rates on non-transport related emissions have failed to increase by more than 10 €/tCO_2 (11 US$/$tCO_2$) in all regions other than the European countries of Denmark, the Netherlands and Switzerland.

Carbon tax – A carbon tax is one directly linked to the level of CO_2 emissions, providing certainty with regards to the marginal cost faced by emitters. It does not guarantee a maximum level of emission reductions, unlike an emissions trading scheme. Norway introduced a carbon tax in the oil and gas production sector in 1991 which has proved to be successful in incentivising the development of the Sleipner and Snøhvit CCUS projects. The cost of injecting and storing CO_2 for the Sleipner project at 17 US$/$tCO_2$ was less than the 50 US$/$tCO_2$ tax penalty levied at the time for CO_2 separated from natural gas and vented to the atmosphere (Herzog, 2016). This was complemented by a commercial need to separate the CO_2 from natural gas to meet gas quality requirements, providing a clearer business case to invest in CCUS.

Carbon taxes have been introduced in several countries (World Bank, 2019), although there are typically exemptions for the different types of emitters, particularly those which participate in emissions trading schemes. These range from as low as 2 US$/t$CO_2$ up to 125 US$/t$CO_2$ as shown in Figure 23.



The size of the circles is proportional to the amount of government revenues except for those with revenues below US$100 million in 2018.

Figure 23 Carbon tax prices introduced globally (World Bank, 2019)

In general, carbon tax systems have not led to CCUS, particularly in the power sector, other than the Norwegian projects noted above. CCUS power plants derive additional revenue from the system only in so much as the carbon tax penalty increases the marginal power prices through unabated fossil fuel plants setting the price. This has typically driven fuel switching from coal to gas, but it could be interesting in countries such as China where there is limited natural gas infrastructure.

Emissions Trading Schemes – Regulation of emissions has also played a role in supporting the deployment of CCUS by placing an implicit value on emissions. A mandatory condition for the approval of the Gorgon project in Australia was the injection of at least 80% of the CO_2 vented by natural gas processing operations. As one of the largest natural gas projects in the world, the additional costs of compressing and storing CO_2 were manageable in the context of the project as a whole, adding less than 5% to the total project costs. The expectation of a future tax on carbon is an additional reason for CCUS being adopted for the Gorgon project, highlighting the point that it is not just current policies but also expected future ones that drives CCUS investment.

In Europe, the latest EU ETS review in 2018 strengthened the Market Stability Reserve (the mechanism to reduce the surplus of emission allowances) and increased the pace of emissions cuts. The overall number of emission allowances will decline at an annual rate of 2.2% from 2021 onwards, compared to 1.74% currently. This review has delivered a stronger carbon price, which fluctuated at around €25 (US$28) for most of 2019. Another element added during the 2018 revision, is the establishment of the €10 billion Innovation Fund, which the pipeline of European CCUS projects will be able to utilise (GCCSI, 2019a; EU, 2018, 2019).

6.1.3 Capital grants

CCUS facilities represent large capital investments. The capital structure of selected CCUS facilities in operation including the coal power plants at Boundary Dam and Petra Nova are shown in Figure 24. Several facilities including these two, have received capital grant support from governments to bridge funding deficits. Bringing new energy technologies to market is challenging because of the so-called 'valley of death' where financing is difficult to obtain for innovations that are not technically proven at high TRL levels (Sloss, 2019). Funding from government grants helps to address this, by rewarding early projects for the knowledge they create which can be used later by subsequent project developers, and by making investments more attractive to private sector investors. Considering Petra Nova, the capital for the CCUS facility was approximately US$635 million. A new 240 MW project based on Petra Nova capturing about 1.4 $MtCO_2/y$ for EOR could be eligible for 12 years of 45Q tax credits that would be worth approximately US$588 million, improving the rate of return on investment and reducing financing risk (CIAB, 2019).

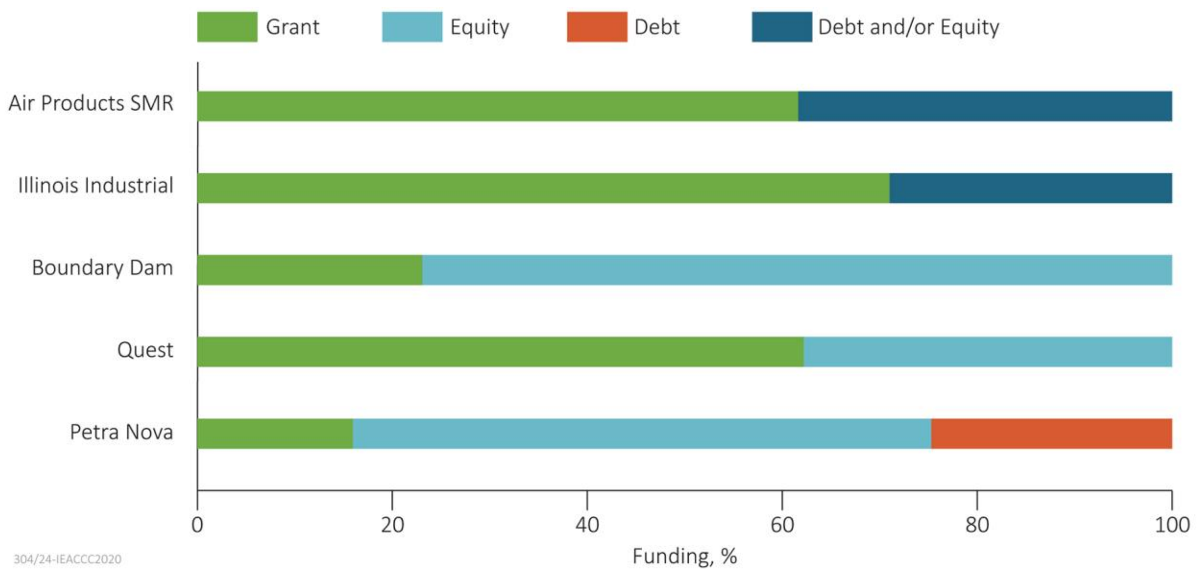


Figure 24 Level of grant funding provided for CCUS demonstration projects (Zapantis and others, 2019)

Grant support has also been used to fund the construction of transport and storage networks, to address cross-chain risks. This was the approach used for the Alberta Carbon Trunk Line, which has received CAN$558 million (US$400 million) from the Alberta and Canadian governments. The 240 km pipeline has been oversized, so that the volume of CO_2 transported can increase over time as more emitters use the transportation network.

6.1.4 State ownership of CCUS facilities

Some governments have overcome the need to attract private sector investment by supporting the construction of CCUS facilities through state-owned enterprises (SOE). In effect, the governments of Saudi Arabia and the UAE have adopted a strategy of state ownership of CCUS facilities to supply CO_2 for EOR, at least in the early stages of deployment. China has also supported CCUS in this way through the state-owned China National Petroleum Corporation for the Jilin project, although it has also implemented other policy measures to support CCUS deployment in China. Sponsoring projects through SOE has several advantages:

- it is a way of directly supporting the development of new industries such as CCUS, particularly in countries that have less developed regulatory frameworks or where outsourcing to the private sector is difficult;
- governments can generally borrow at relatively low interest rates, helping to bring down the effective cost of capital for projects; and
- the development of transport and storage infrastructure is particularly suited to this funding approach due to its naturally monopolistic characteristic.

6.2 ADDITIONAL MEASURES

To date, CCUS has been deployed in relatively few countries and in general has relied on the revenue stream from EOR, although there have been a few exceptions including Sleipner, Snøhvit, Quest, Gorgon, and In Salah (*see* Table 2 for project details).

While this has enabled the initiation of projects, the policies currently in place are insufficient to enable CCUS deployment to scale-up at the rates required to meet global climate targets (GCCSI, 2019a; Kapetaki and Scowcroft, 2017; Billson and Pourkashanian, 2017). In addition to the features described in Section 6.1, the additional measures are required and described below.

6.2.1 More favourable debt and equity financing

For capital intensive investment projects such as CCUS facilities, the cost of debt and equity can have a significant impact on its financial viability. Banks have a critical role in providing debt finance which must increase significantly in order to achieve the necessary growth in the number of CCUS projects. To qualify for debt financing, CCUS projects will need to provide assurance that key risks are identified with mitigations in place and that hard to manage risks are allocated to government in the short term. This is because equity investors require higher rates of return on higher risk investments loans. Whilst the Petra Nova coal based CCUS project was able to attract debt financing on the back of EOR revenues, wider roll-out requires a policy framework that reflects the value of CO_2 in the context of emissions reductions targets as noted in Section 6.1.2

The different sources of financial instruments and their advantages and disadvantages are shown in Table 10, noting that project financiers will typically utilise a range of financial instruments to reduce project risk exposure. Some of these institutions specialise in high risk environments, including in developing countries.

TABLE 10 FINANCIAL INSTITUTIONS AND INSTRUMENTS (ZAPANTIS AND OTHERS, 2019)

Source	Description	Advantage	Disadvantage
Commercial debt	Asset-backed loans that can be secured over the medium to long-term Commercial debt has been an important source of finance for both fossil fuel and renewable energy projects	Flexible and capable of providing a significant proportion of funding (high liquidity)	Time consuming and uncertainty execution Not attracted to new technologies and will tend to perceive these as risky
Green Banks	Banks specifically targeting green or low carbon investment	Deep liquidity Able to provide policy and technical support	Limited in scope and may not have support for CCS Region specific
Investment Insurance Agency or Export Credit Agency	Government or private financial institutions that can offer financing to domestic company international operations. They help to resolve risks such as export and political risks of overseas investments	Reduces risks	Backed by assets Requires a well-defined strategy employed during the early stage of project design
Multi-lateral Banks/ International Financial Institutions	This includes multilateral development banks (serving developing countries) and multilateral financial institutions (specialising in types of projects rather than regions). They play a significant role in Climate Finance as many of them serve as accredited entities to the Green Climate Fund. They have a long history of providing direct lending to projects	Deep liquidity Typically better than commercial bank's lending conditions as they are often able to provide concessional financing Able to provide substantial technical and policy support	Region specific and may not support CCS based on eligibility criteria

The cost of equity is also affected by risk. Typically, an investment is made if the expected internal rate of return (IRR) is equal to or greater than the required rate of return, known as the hurdle rate, where it will be generally set higher for higher risk investments. For CCUS, with a perceived high risk, this represents a problem. To date, to help overcome the barrier, governments have typically provided capital grants as well as other mechanisms to aid financing such as loan guarantees and tax exemptions (Lockwood, 2018a). These funds are usually made available during the construction phase, before a final investment decision. As more CCUS facilities come online and the industry matures, the relationship between IRR, hurdle rate and the requirement for policy support in the form of capital grants is expected to change as shown in Table 11.

TABLE 11 SIMPLIFIED FINANCIAL MODELLING FOR CCUS PROJECTS (ZAPANTIS AND OTHERS, 2019)

Source	Early stage projects	Medium stage projects	Mature stage projects
Capital cost, US$ millions	800	60	500
Grant contribution, %	65	30	0
Equity contribution, %	35	40	30
Debt contribution, %	0	30	70
Cost of debt, %	14	10	4
Hurdle rate, %	17.5	10	8
Cost of CO_2 transport and storage, US$/t$CO_2$	20	12	5

As the market matures, with the steps identified already in this section increasingly in place, the hurdle rate will fall from 17.5% towards 8%, with the cost of debt falling from 14% towards 4%. As the CCUS industry matures, risk reduction is making lower cost finance more available, which in turn reduces the cost of investments. In the mature market stage, projects tend to comprise exclusively of equity and debt capital (Zapantis and others, 2019).

6.2.2 Reducing risks

Some of the key risks for CCUS projects are highlighted in Table 12 below (Zapantis and others, 2019), which indicates that the risk premium for CCUS projects is currently around 11%. When added to a standard low risk project debt financing rate of 4%, this brings the debt rate for CCUS projects currently to around 14–15%. Although the numbers in this table are not absolute in terms of the impact or risk on debt lending rate, it shows where the development and prioritisation of policies should be focused to give greatest cost reduction. As noted earlier, these risks must be reduced in order to lower the debt lending rates for CCUS projects.

TABLE 12 PERCEIVED RISK FOR CCUS PROJECTS (ZAPANTIS AND OTHERS, 2019)

Perceived risk	Risk category	Probability	Consequence	Risk rating	Debt rate risk premium, %
Cross-chain	Hard to reduce	5	5	25	2.7
Policy and revenue	Hard to Reduce	4	5	20	2.2
Storage liability	Hard to reduce	2	5	10	1.1
Leakage	General project risk	2	5	10	1.1
Stranded asset	General project risk	2	5	10	1.1
Political risk	General project risk	2	3	6	0.7
Project financing	General project risk	1	4	4	0.4
Market design and regulation	General project risk	1	3	3	0.3
Social acceptance	General project risk	1	3	3	0.3
Operating and performance	General project risk	1	3	3	0.3
Legal system	General project risk	1	3	3	0.3
Construction	General project risk	1	2	2	0.2
Administrative risk	General project risk	1	2	2	0.2
CCUS risk premium					10.9

In brief, the key risks identified as 'hard to reduce' which should be addressed in the near term by transferring to governments include:

Cross-chain risk – While the separation of the capture, transport, and storage elements of CCUS is considered the most likely model, it introduces challenging 'cross-chain' risks, where there is a chance that one party in the supply chain defaults on its obligation to supply or take CO_2, affecting the other parties in the chain (CCSA, 2016; IEA, 2016). A greater role for government in taking on the risk could alleviate this problem, or at least provide a clear structure to allocate risks between the various entities.

Policy risk – The potential for changes in political support poses a risk for any CCUS investment which is directly dependent on government policy for its commercial viability. Changing incentives for renewables in some countries has damaged investor confidence in this sector and investors may perceive an even greater risk for CCUS where there has been a history of changing political support (Lockwood 2018a). Many projects have been started under supportive conditions only to see waning political backing before they have proceeded to a final investment decision (FID). The history of CCUS in the UK presents a clear example of how political uncertainty can harm investor confidence (CCSA, 2016; Lockwood 2018a).

Storage liability – While the risk of CO_2 leaking from geological storage is low, the impact is a cost to the project which is difficult to quantify. Leakage risks could feasibly be covered by government, as recognition of the broader value of CCUS to society. The IEA have proposed that national governments are best placed to bear 'climate related leakage risks' while project operators retain responsibility for any local environmental impacts or health and safety issues relating to a potential leak (IEA, 2016). This is based on the rationale that only the government has the means to instigate 'climate compensation' tools beyond the sphere of the project, such as increased deployment of renewables. One model adopted by the Australian Government is where the storage operator retains the risk of short-term liability during the operational period of the project and for a specified post-closure period (Dixon and others, 2015). This approach has been replicated elsewhere including the EU and Alberta, Canada. The basis is that the risk of leakage is highest during the CO_2 injection phase, which reduces the post-injection phase risk and continues to reduce over time. Consequently, the long-term risk accepted by government should be low.

6.2.3 Hub and cluster approach

Shared transport and storage networks can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk (IEA, 2017; Zapantis and others, 2019; CCUS Cost Challenge Task Force, 2018). Heavy industries often exist in clusters close to local resources, power generation supply and port or rail infrastructure. These industrial clusters can be supported by providing CO_2 transport and storage network infrastructure which multiple CO_2 sources can access. This reduces the unit cost of CCUS as the CO_2 network capital cost is spread out across an increased quantity of CO_2. It also reduces cross-chain risk by creating multiple customers for the operators of the CO_2 transport and injection business and multiple CO_2 storage service providers for industrial CO_2 sources. This provides greater levels of operational flexibility than single source and sink facilities and reduces the operational risk.

As noted in Section 4.2.2, the hub and cluster approach is driving the way CCUS projects are now being carried out in Europe. Capturing CO_2 from clusters of industrial installations, instead of single sources, and using shared infrastructure for the subsequent CO_2 transportation and storage network, is seen as the preferred approach to drive down unit costs across the CCUS value chain. Examples include Port of Rotterdam in the Netherlands (Porthos, 2019), the Northern Lights project in Norway (Northern Lights, 2019) and the six UK industrial decarbonisation pre-FEED projects (*see* Table 13), as announced in the Industrial Strategy Challenge Fund phase 1 competition (UKRI, 2020). The six UK projects will be able to compete for a total of up to £131 million in phase two of the competition, for projects that will deliver, or support delivery of significant emissions reductions in a UK industrial cluster by 2030.

TABLE 13 UK INDUSTRIAL DECARBONISATION DEMONSTRATION PROJECTS (UKRI, 2020)

Project	Region	Description
Scotland's Net Zero Infrastructure	Scotland	This project enables CCUS by linking the gathering of CO_2 from industrial emitters around Grangemouth, with a pipeline to transport CO_2 to St Fergus in Aberdeenshire, with the Acorn CCS Project.
Net Zero Teesside Project	Teesside	In partnership with local industry and world class partners, Net Zero Teesside aims to decarbonise a cluster of carbon-intensive businesses by as early as 2030. The project plans to capture up to 6 $MtCO_2/y$.
Humber Industrial Decarbonisation Deployment Project (Humber-DP)	The Humber	Humber-DP will identify and develop potential anchor projects to maximise emission reductions in the most appropriate, timeliest, cost effective and efficient manner and develop world leading industrial CO_2 transport and storage system.
HyNet Carbon Capture Utilisation and Storage (CCUS)	North West	HyNet was conceived in 2016 as a hydrogen/CCUS project to provide a decarbonisation pathway in the North West. The HyNet CCUS network will provide the infrastructure to transport and store the CO_2 produced as a by-product of the hydrogen production process.
South Wales Industrial Cluster (SWIC)	Wales	SWIC will identify process options to reduce carbon emissions, options for CCUS and options for an infrastructure backbone to enable large-scale CO_2 emissions reduction across Wales and beyond.
Green Hydrogen for Humber	The Humber	Green Hydrogen for Humberside will lead to the production of renewable hydrogen, at the GW-scale, from polymer electrolyte membrane (PEM) electrolysis. This will be distributed to a mix of industrial energy users in Immingham, Humberside. Humberside, the UK's largest cluster by industrial emissions (12.4 $MtCO_2/y$), contributes £18 billion to the national economy each year and has access to a large renewable resource from offshore wind in the North Sea.

The same hub and cluster approach was also used in the Shand FEED study (Int CCS KC, 2018) where the CO_2 is used for EOR. EOR operators require reliable sources of CO_2 to avoid interruptions in oil production, so connecting two or more CO_2 sources to an EOR operation reduces the potential operating risk. A further example of this CO_2 hub concept is the Alberta Carbon Trunk Line (ACTL) in Canada which is large enough to transport 14.6 $MtCO_2/y$ in its 240 km pipeline with the transported CO_2 utilised for EOR and geological storage.

The initial investment in the hub and cluster model could also be a barrier, unless guarantees are provided for revenue during the early stages of development. In the UK for example, the Regulated Asset Base (RAB) model has been used to enable private investment in infrastructure (CCUS Cost Challenge Task Force, 2018). RABs use a legally binding license with a periodical regulatory review of long-term tariffs. In this setup, all investments made are valued and costs are recovered from consumers under regulation. The consumers effectively cover the risks, which in turn shelters investors from exposure to them and facilitates their investment. This RAB funding approach has been proposed for the UK CCUS transport and storage infrastructure, as described in the next section.

Where the balance of risk and return is still insufficient for initial private sector investment in the CO_2 transport and storage network, the relevant government should consider taking this role. In this way, governments can kickstart a hub and cluster development with the option of privatising the business after it has gained sufficient CO_2 source and sink 'customers'. Alternatively, the relevant government could invest in establishing a regulatory framework that provides the private sector with the right incentives to invest in transport and storage networks, which may be preferable in regions where this is already common practice for infrastructure projects (Zapantis and others, 2019).

6.2.4 Potential business models

Several potential business models that incorporate the features described earlier in this section have been proposed (ElementEnergy, 2018; CCUS Cost Challenge Task Force, 2018). The preferred business model for the UK case as proposed by the CCUS Cost Challenge Task Force is shown in Figure 25.

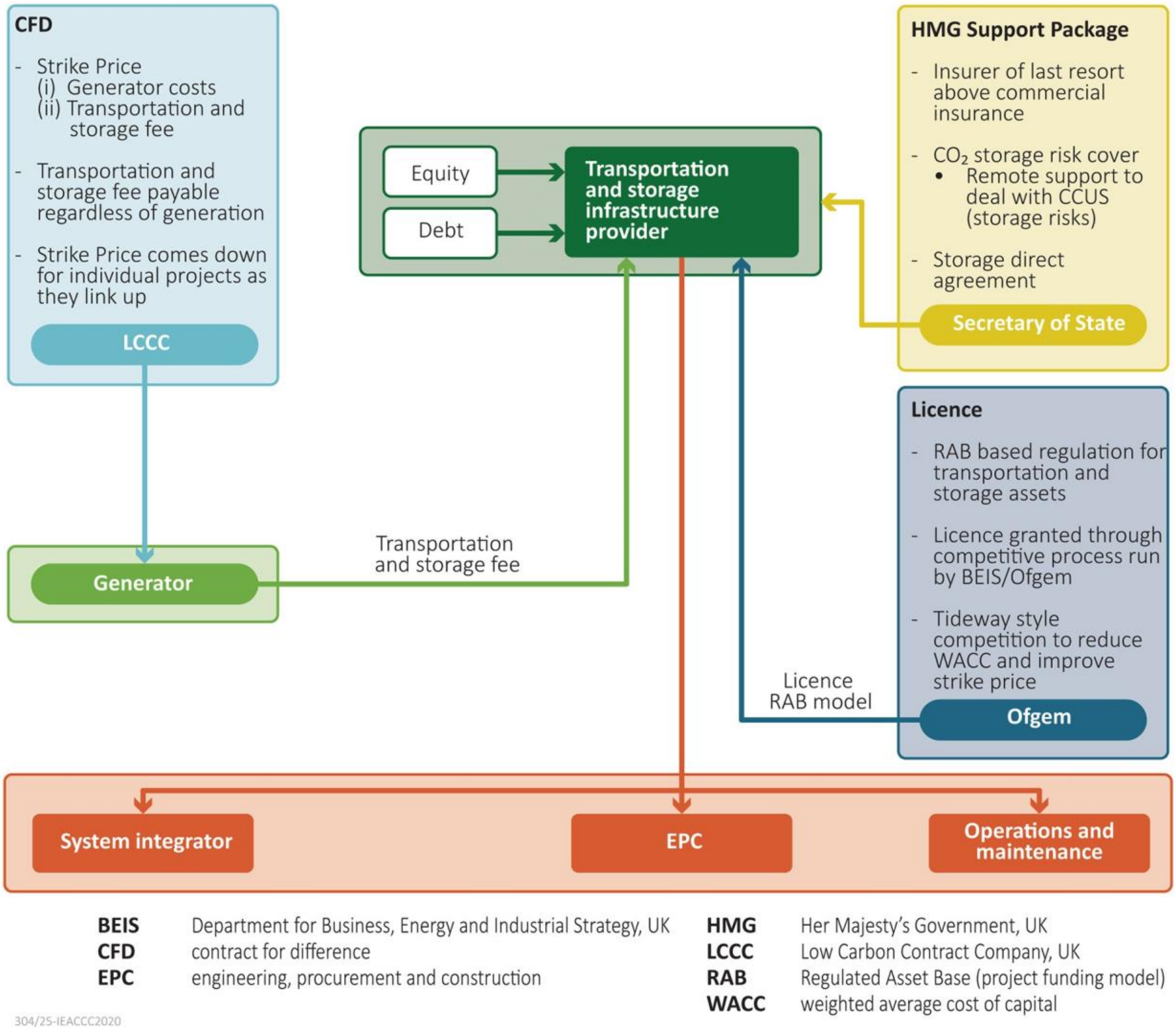


Figure 25 Potential business model for CCUS as proposed in the UK (CCUS Cost Challenge Task Force, 2018)

Transport and storage (T&S) – the model is based on the use of the Regulated Asset Base (RAB) for the T&S component of the CCUS project. The RAB model gives the flexibility to enable future development as the need for further infrastructure increases and is potentially attractive to investors with a longer-term time horizon. RAB models have low volatility in returns, a stable regulatory regime and the potential for future growth and deployment of further capital. RAB models therefore command a lower cost of capital which helps drive down the overall costs of delivery. In the UK case, the regulator for electricity and natural gas markets, Ofgem, could regulate the T&S assets economically through the grant of a license for CCUS T&S and would determine the T&S fees for the T&S licensee through a system of regulatory building blocks set out in the license. There would be a duty on the regulator to ensure that the T&S provider was able to finance its functions. This would include the design, construction, financing, operation, maintenance and decommissioning of the T&S assets, including its monitoring obligations.

Capture for electricity generating projects – the model proposes that CO_2 capture-related projects which generate electricity could be supported using the existing UK Contract for Difference (CfD) mechanism, or any successor mechanism that may be introduced in the future. CfD is the government's main mechanism for supporting low-carbon electricity generation. CfDs incentivise investment in energy projects by providing developers of projects with high upfront costs and long lifetimes with direct protection from volatile wholesale prices. At the same time, they protect consumers from paying increased support costs when electricity prices are high.

The UK Energy Act 2013 (Energy Act, 2013) provides the legislative foundation for the CfD regime and sets out that for CCUS, CfDs can be awarded by the Secretary of State for BEIS through bilateral negotiation rather than competitive auction. In the future, the UK Government should consider whether CfDs for CCUS projects could be awarded through a competitive process.

The CfD strike price for CCUS would need to reflect the cost of capture and generation as well as the relevant project's proportion of the CO_2 transport and storage fee. However, the transport and storage fee could be a separate pass-through element of the overall revenues and not part of the CfD strike price (CCUS Cost Challenge Task Force, 2018; Billson and Pourkashanian 2017).

The UK's CCUS Advisory Group (CAG) proposed a variant of the CfD to take account of the dispatchability of CCUS (CAG, 2019). Referred to as 'dispatchable CfD', this would include fixed and variable payments designed to bring forward investment in dispatchable low-carbon generation capacity, including electricity generation with CCUS. The models is an adaption of the standard CfD mechanism described above which aims to enable CCUS to play both a baseload and mid-merit role in meeting electricity demand. The design of the dispatchable CfD is intended to ensure that electricity plants with CCUS would dispatch ahead of unabated gas-fired plants, but behind renewables and nuclear generation, thereby acting as a key source of low-carbon flexibility. The contract length would need to recognise the expected long life of new CCUS plant, with the CGA recommending that the dispatchable CfD contracts should run for at least 20 years. This would reduce the annual level of revenue support required, underpin the investment in the initial T&S infrastructure and make project financing more manageable.

The CAG also concluded that there are several suitable variations to the business model shown in Figure 25 which should also be considered, which are:

- provide a grant to cover the initial capital cost of CO_2 transport and storage in a new CCUS cluster;
- initial ownership of CO_2 transport and storage by the Government prior to privatisation;
- extending the CO_2 transport and storage company to cover the whole of the UK under either private or public/government ownership;
- public-private ownership of CO_2 transport and storage; and
- the use of RAB structures for other parts of the CCUS chain.

6.2.5 Grid support and ancillary services

Large fossil fuel power plants incorporating steam and/or gas turbines provide a high level of inertia which plays an important role in overall power grid response, including frequency disruptions, power factor correction and dispatchability (CIAB, 2019). As non-dispatchable renewable energy continues to increase, ancillary services in the form of quick dispatchable backup power will become more important. Coal power plant owners may therefore be able to receive additional compensation for providing backup power, provided that integration of the CCUS facility does not adversely affect the power plants ability to provide these services. A further opportunity may be the ability to shut down the CCUS facility temporarily during periods of high electricity prices to provide additional reactive power to the grid as an ancillary service. Placing a financial value on the provision of these ancillary services would improve the business case for fossil fuelled power plant with CCUS. Indeed, a study by Bechtel of a post-combustion power plant retrofit to a coal power plant in Australia (Bechtel, 2018) showed that this ability would have a major positive impact on the viability of the facility.

6.2.6 Public perception and lack of trust

Public opposition has played a significant role in the cancellation of CCUS demonstration projects, particularly in Europe (Lockwood, 2018a). Concerns expressed were diverse, but often centred on fears of release of CO_2 coupled with a wider opposition to the fossil fuel industry. Generally, it has been found that appropriate selection of project location and a strong stakeholder communications strategy can avoid opposition to CCUS demonstration plant from local communities, politicians, or other groups. However, the early experiences of project cancellations, particularly in Europe, has made the CCUS technology providers cautious of public opposition. This may have deterred some investors and limited the number of onshore storage sites which can be considered (Lockwood, 2017).

The issues of low general public awareness of CCUS and lack of support for the technology as part of an integrated approach to minimising the impact of power generation on global temperature, presents a longer-term problem for CCUS. A key issue is a lack of trust between the general public and technical experts presenting the CCUS message, which have often been from the coal and/or oil and gas industry sectors (GHGT, 2018). These sectors are perceived as having a vested interest, using CCUS as a means to continue to operate their industries. There is also a general distrust of governments, by both CCUS technology providers and the public, where CCUS projects and funding competitions have in the past been cancelled as noted above. What is required is CCUS champions or grouping of champions such as investors and non-governmental organisations, to provide complementary reasons for the need for CCUS across a spectrum of interests. International organisations with perceived neutrality such as the IEA and IPCC will also have a key role to play in this regard. As noted by (Xenias and Whitmarsh, 2018), there is also room to improve the flow of learning from the public engagement research literature to the champions and organisations charged with delivering the CCUS message.

6.2.7 Proving CO_2 storage in developing countries

There has been limited interest in CCUS in countries like India, due in part to a relatively poor understanding of geological CO_2 storage data there, as noted in Section 4.2.4 (Gupta and Akshoy, 2019). A comprehensive national study on Indian storage basins is therefore needed to support the potential for CCUS demonstration in India and this is likely to be the case in most developing countries as the roll-out of CCUS accelerates. The IEA also notes that co-ordinated and extensive CO_2 storage assessment programmes are required in all key regions, which should start as a matter of urgency, given the long lead times in developing CO_2 storage (IEA 2017).

6.2.8 Increase R&D spending

As noted by the IEA (2017), there has been a trend of decreasing CCUS-related public RD&D investment in recent years, although there are signs that this is now starting to reverse. One example is the EU's new Innovation Fund with around €10 billion (around US$11 billion) proposed to be made available, when 450 million EU ETS allowances are auctioned in 2020-30 (EU, 2019). Overall, the level of global R&D investment needs to increase to address the CCUS technology research priorities as defined in Chapter 3.

A further example is the US DOE which continues to invest in next generation R&D, having selected seven projects in 2018 to receive US$44 million through the funding programme '*Design and Testing of Advanced Carbon Capture Technologies*' (US DOE, 2018).

6.3 SUMMARY

More positive carbon price signals would drive growth in CCUS. Whether the carbon price is effectively valued through carbon emitted, emissions trading schemes or tax credits on the amount of CO_2 stored, the value needs to be around 40–80 US$/t$CO_2$ in 2020, increasing to 50–100 US$/t$CO_2$ by 2030.

The hub and cluster approach should be adopted to enable the sharing of transport and storage networks. This can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk. Fossil fuel power plants with CCUS could form the anchor for these clusters with local industries feeding in their captured CO_2.

The availability of debt financing for CCUS projects needs to increase significantly and banks have a critical role to play. To qualify for debt financing, CCUS projects will need to provide assurance that key risks are identified with mitigations in place and that hard to manage risks are allocated to government in the short term.

7 SUSTAINABLE DEVELOPMENT GOALS

The United Nations has set 17 Sustainable Development Goals (SDGs) with the number of targets contained within them totalling 169. The SDGs cover a broad range of social and economic development issues and whilst they are broadly interrelated, each has its own targets to achieve (*see* Figure 26).

Figure 26 United Nations Sustainable Development Goals (https://sustainabledevelopment.un.org/)

This report has assessed the role of CCUS to support the transition to a net zero emissions future, but this transition should also be seen in the wider context of the UN SDGs. Indeed, the global climate policy and the SDGs are interconnected, as the way the climate problem is addressed strongly affects the prospects of meeting a number of the SDGs (Stechow and others, 2016). The Sustainable Development Scenario of the IEA's World Energy Outlook, for example, lays out a pathway to reach the SDGs most closely related to energy (IEA, 2019a):

- achieving universal energy access (SDG 7);
- reducing the impacts of air pollution (SDG 3.9); and
- tackling climate change (SDG 13).

There are still around one billion people globally, primarily in the continents of Africa and Asia, who do not have access to electricity. As the living standards of these regions increase, they will seek to use indigenous energy sources such as solar, wind and biomass renewables, as well as coal. Therefore, the combined approach of limiting global temperature rise (SDG13), whilst providing access to reliable and affordable energy (SDG7) to support economic development and improved living standards is important. This forms part of an 'inclusive transition' where OECD countries need to work with developing nations to move towards a lower emissions future that does not disadvantage any section of the global population.

The IPCC have performed an in-depth analysis of the interaction of achieving the Paris Agreement targets with the SDGs in Chapter 5 of their report on 'Global warming of 1.5°C' (IPCC, 2019). It recognises that coal with CCUS plays an important role in deep mitigation pathways. If the world is to succeed in constraining CO_2 emissions to levels consistent with a less than 2°C rise in global temperature, excluding CCUS would increase the cost of doing this by 138%.

A brief review of the most heavily impacted SDGs from the introduction of CCUS is provided in Table 14.

TABLE 14 IMPACT OF COAL CCUS ON SDGS (IPCC, 2019; STECHOW AND OTHERS, 2016)

SDG3: Disease and Mortality	CCUS technologies have the capacity to reduce atmospheric pollutants, particularly sulphur and nitrogen oxide emissions, fly ash and heavy metals (mercury). The reduction in efficiency of coal-fired power plants fitted with CCUS relative to unabated coal plant on the other hand, could mean that local air pollution is potentially exacerbated. There is also a low risk of CO_2 leakage from geological storage or the CO_2 transport infrastructure from source to sequestration location. However, offset against this is the significant risk of increased mortality through not achieving net zero GHG emissions by 2050 if CCUS is not pursued (*see* SDG 13 below)
SDG6: Water Efficiency and Pollution Prevention	CCUS typically requires access to water for cooling and processing which could contribute to localised water stress. However, CCUS processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration and use of air or hybrid cooling (*see* Section 5.7)
SDG7: Affordable and clean energy	Advanced and cleaner fossil fuel technologies are in line with the targets of SDG7. The United Nations Economic Commission for Europe (UNECE) for example is working with countries and industry to reduce the ecological footprint of fossil fuels. This includes disseminating best practices for deploying high efficiency, low emissions fossil technology with CCUS, to help ensure energy access and promote investment in new technologies.
SDG8: Decent work and economic growth	The adoption of CCUS allows countries with indigenous coal reserves to use those reserves, along with renewables, to achieve economic growth whilst also meeting climate action in line with SDG13. The IPCC noted a risk that the continued use of fossil fuel, enabled in part through CCUS, could lock-in human and physical capital in the fossil resources industry (IPCC, 2019).
SDG13: Climate Action	Most climate models indicate that to achieve the 2°C temperature target of global temperature rise without CCUS may not be achievable and would increase risk by limiting the potential for large-scale CO_2 removal using BECCS (Stechow and others, 2016; Consoli, 2018). Analysis by the IPCC has estimated that without CCUS, the cost of climate mitigation would increase by 138% (IPCC, 2019).

7.1 SUMMARY

CCUS is a key technology contributing in particular to SDG13 – Climate Action, as part of the transition to a net zero CO_2 emissions future.

8 CONCLUSIONS

This report has looked at the status of CCUS globally, assessing the barriers that have prevented its wider-scale deployment and considered the potential steps that need to be taken to roll-out the technology at commercial scale in line with future net zero emissions requirements. The key conclusions that can be drawn from this review are outlined below.

In terms of the need for CCUS:

- Fossil fuel power generation fitted with CCUS is a key part of the transition to a future net zero CO_2 emissions world by the second half of this century. Some 170 GWe of coal-fired power generation with CCUS would be needed in order to limit the global temperature rise to 2°C or less. This could be new-build power plant including CCUS at the outset, or more likely, CCUS retrofits of existing coal power plant.

- The Asia Pacific region accounts for more than 50% of global CO_2 emissions, driven by rapidly growing economies. It is also responsible for over 70% of global fossil fuel consumption. This region should become a key focus for the roll-out of commercial CCUS. Retrofit of a portion of the existing young power fleet will be necessary and any new build coal power plant should be built 'capture ready', to reduce the risk of becoming stranded assets.

- CCUS is a key technology contributing in particular to SDG13 – Climate Action, as part of the transition to a net zero CO_2 emissions future. A combined approach of limiting global temperature rise, whilst providing access to reliable and affordable energy to support economic development and improved living standards should be pursued.

In terms of the technical status of CCUS and the lessons learned from the coal-fired CCUS demonstrations:

- From a technical viewpoint, there are no insurmountable hurdles for CCUS, as a number of the component technologies for capture, transport and storage are readily deployable at commercial scale (TRL9). Several other next generation technologies that could provide step change cost reductions and increase efficiency are being researched and developed and could in time be on the market.

- The cost of CCUS, which is probably the single most important lever for wide-scale roll-out of the technology, has reduced significantly. Petra Nova, the second large-scale operational CCUS facility built in 2017 has a cost of CO_2 capture which is 38% lower than the Boundary Dam CCUS facility built around three years earlier. A more meaningful comparison is that of the Boundary Dam CCUS facility with the Shand FEED study, where a cost reduction of 57% is projected for a single 300 MWe coal power plant with 90% CO_2 capture. This would take the cost down to 45 US$/t$CO_2$ removed, with capital cost and variable operating and maintenance costs being the key areas for achieving this reduction. The Shand FEED study fits into a cluster of more recent project studies at around the 43–45 US$/t$CO_2$ removed cost level, within a proposed timescale for commencement of plant operations by 2024-28. Further cost reduction for subsequent CCUS facilities through 'learning by doing' will be achieved where a learning rate of 8–13% and assuming a target capacity of 170 GWe of coal-fired power plant fitted with CCUS, could reduce the cost for amine-based post-CO_2 removal by 50–70% by 2050 from the current cost of around 65 US$/t$CO_2$.

- Availability of the power plant was an issue in the early CCUS demonstrations, but it has now reached acceptable levels. For example, the Boundary Dam CCUS facility has increased its availability to around 85% over the last two years, in line with the facility's design availability of 85%. This is acceptable for a demonstration project, but availability will need to continue to improve to move towards power plant industry standards, where NGCC power plant can now operate at availability levels in excess of 90%.

- CCUS capture levels will need to increase from the current 85-90% to closer to 100% to allow the power plants to continue to operate in a net zero emission future as any residual CO_2 emissions from CCUS facilities will not be compliant without offset from negative CO_2 emissions elsewhere. Where auxiliary plant are used to provide steam and energy for the CCUS facility, they will also need to include CCUS to achieve very high capture levels overall. Such high capture efficiencies are technically possible, but at higher capital cost and an increased cost of electricity. The concept of cofiring a coal power plant with around 10% biomass and utilising 90% CO_2 capture levels to achieve net zero emissions could be a solution (ETP, 2014). This would be particularly interesting as a relatively easy means of incorporating renewable electricity in countries with indigenous coal and forestry or agricultural waste materials. Increased cofiring of biomass would potentially enable a fleet of CCUS cofiring coal-fired plant to move to negative CO_2 emissions in the second half of the century. This would increase flexibility in the measures required to achieve a below 2°C temperature rise target.

In terms of the next steps to achieve the required commercial roll-out of CCUS:

Despite the cost reduction that has been achieved to date, CCUS has been deployed in relatively few countries and in general has relied on the revenue stream from EOR. While this has enabled the first wave of demonstration projects to get off the ground, the policies currently in place are insufficient. The following actions would facilitate the deployment of CCUS:

- More positive carbon price signals would drive the growth in CCUS. Whether the carbon price is effectively valued through carbon emitted, emissions trading schemes or tax credits on the amount of CO_2 stored, the value needs to be around 40–80 US$/t$CO_2$ in 2020, increasing to 50-100 US$/t$CO_2$ by 2030. Currently, less than 5% of global CO_2 emissions have a carbon pricing regime which is consistent with this.

- The hub and cluster approach should be adopted to enable the sharing of transport and storage networks. This can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk. Fossil fuel power plants with CCUS could form the anchor for these clusters with local industries feeding in their captured CO_2. There is however likely to be an initial investment barrier to the shared hub and cluster infrastructure where the balance of risk and return is insufficient for initial private sector investment. In this case, the government could consider taking this role to kickstart a hub and cluster development.

- The availability of debt financing for CCUS projects needs to increase significantly and banks have a critical role to play. This is because, for capital intensive investment projects such as CUCS facilities, the cost of debt and equity can have a significant impact on a project's financial viability. To qualify for debt financing, CCUS projects will need to provide assurance that key risks are identified with mitigations in place and that hard to manage risks are allocated to government in the short term. The cost of debt will need to reduce from the current 14–15% level to closer to less than 10% in the medium term, as successive CCUS projects are able to address risk and drive down the cost of debt risk premium.

- Governments could send a much stronger message on the value of CCUS by explicitly including it in their respective national climate strategies and Nationally Determined Contributions (NDCs) for those countries party to the Paris Agreement.

- System and network operators could recognise the value of auxiliary services such as reactive power and frequency response provided by coal powered plant and allow for financial compensation for these services. Such services will become increasingly important as the share of non-dispatchable renewable power sources, primarily wind and solar, increase in global power systems. The integration of a CCUS facility must therefore not adversely affect the power plant's ability to provide these services.

- A co-ordinated CO_2 storage assessment programme is required, particularly in developing countries with indigenous coal reserves, which given the long lead times in developing CO_2 storage, should start urgently.

- CCUS champions or grouping of champions such as investors and non-governmental organisations need to be in place and active, to provide complementary reasons for the need for CCUS across a spectrum of interests. This is because technical experts presenting the CCUS message to date, have often been from the coal and/or oil and gas industry sectors, who the public perceive as having a vested interest in perpetuating fossil fuel based power generation and industry.

In summary, CCUS is a proven technology with costs on a strong downwards trajectory. It is a key part of the transition to a future net zero CO_2 emissions world which now needs a strong financial and regulatory regime to achieve commercial roll-out.

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