Learning by doing:

The cost reduction potential for CCUS at coal-fired power plants

November 2019

INTERNATIONAL CCS KNOWLEDGE CENTRE

CIAB

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Coal Industry Advisory Board Submission to the International Energy Agency

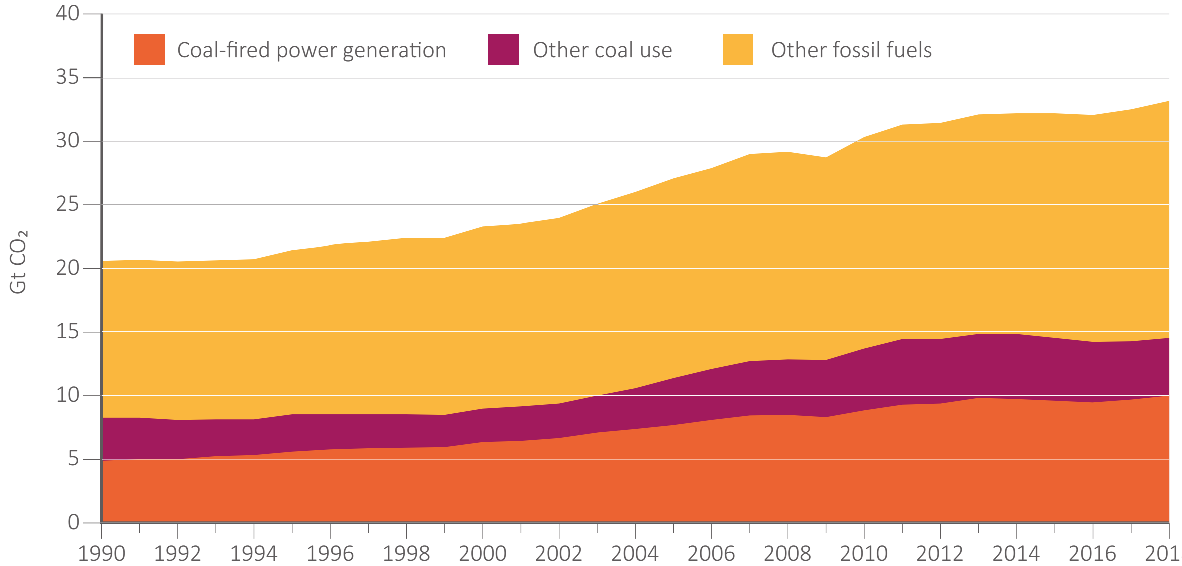
November 2019

Executive Summary

The 2015 United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement limits the increase in global average temperature rise to well below 2°C above pre-industrial levels. To meet this target, large-scale, emissions-intensive, industrial and power generation processes must be significantly decarbonized. Reductions of this magnitude cannot be achieved without accelerated progress in the commercial-scale deployment of carbon capture, utilization and storage (CCUS) across a wide variety of applications, including coal and natural gas-fired electricity generation; industrial processes, such as steel and cement manufacturing; fossil fuel-derived hydrogen generation; and bioenergy production. In the lowest-cost scenario of the 2018 World Energy Outlook (WEO), the International Energy Agency (IEA) estimates that CCUS could contribute 13% of cumulative emission reductions required leading up to 2060. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that realizing a 2°C limit would be more than twice as expensive without CCUS, equating to an incremental 3% of cumulative global GDP through to 2100. Failure to implement CCUS broadly across all industries on a global scale would make realizing a 2°C outcome unlikely.

Coal represents a significant share of global CO_2 emissions (*see Figure 1*) and is projected to account for up to 22% of total primary energy demand by 2040 according to the IEA's 2018 World Energy Outlook (WEO) New Policy Scenario. Over a third of the existing global coal-fired power generation fleet is less than 10 years old, and new coal-fired power plants continue to be built today. The desire for economic return on investment will hinder premature retirement of these facilities.

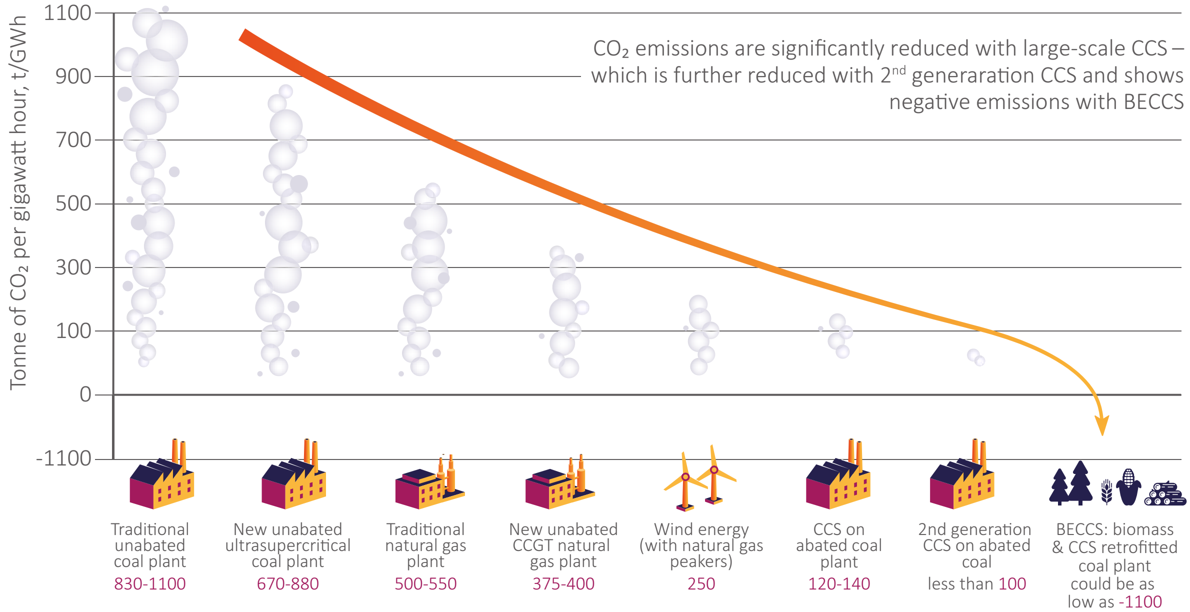
Figure 1: *Global Energy-Related CO_2 Emissions by Source, 1990-2018*



Source: International Energy Agency

Remarkable improvements in the cost and performance of renewable energy technologies (particularly solar and wind power generation) have recently been achieved. Low or zero-emissions power generation with renewable and alternative energy sources is essential to meeting the 2°C limit. Yet, we simply cannot abandon CCUS. Rapid population and economic growth in developing countries, coupled with associated hard-to-abate, but essential, sectors, such as steel and cement manufacturing; alarming rates of deforestation; and growing agricultural activity have all widened the gap between global efforts to reduce greenhouse gas (GHG) emissions and a 2°C pathway. Reductions totaling approximately 760 Gt of CO_2 will be required across the energy sector by 2060, which are equivalent to all energy-associated emissions at 2017 levels produced over a period of more than 20 years. Consequently, every emission reduction technology will be essential to accelerate international efforts to abate atmospheric CO_2 levels. Furthermore, studies have shown that the thermal coal power fleet can provide atmospheric CO_2 reduction through co-firing with biomass in conjunction with CCUS (BECCS) as a negative-emission strategy (*see Figure 2*).

Figure 2: *CO_2 Emissions Reduction Through Large-Scale CCUS Deployment at Power Plants*



Source: International CCS Knowledge Centre

In a 2016 report issued by the Coal Industry Advisory Board (CIAB) to the IEA, entitled *An International Commitment to CCS: Policies and Incentives to Enable a Low-Carbon Energy Future*, governments were encouraged to advance policies in support of encouraging higher rates of CCUS deployment by the industrial and power sectors, in order to meet the 2°C goal. These recommendations are reinforced in the report herein and may be grouped into four categories:

- **STIMULATE CCUS MARKET UPTAKE** by putting into place policies that enable investment capital to earn a market-based rate of return.
- **SUPPORT PROJECT DEVELOPMENT** to close the commercial gap for early projects and accelerate CCUS uptake.
- **ENABLE PROJECT FUNDING** to financially de-risk early CCUS projects.
- **ADVANCE NEXT-GENERATION CCUS TECHNOLOGIES** by funding pre-competitive technology and knowledge development.

Furthermore, in a 2017 CIAB report, entitled *An International Commitment to CCS: Priority Actions to Enable CCS Deployment*, case studies in the United States, the United Kingdom, Australia, and the People's Republic of China were considered in detail to provide policy lessons for other governments and to reinforce the recommendations made in the 2016 CIAB report.

An opportunity to reduce the cost of CCUS exists. This report explores pathways to reduce capital and operating costs. Reduced costs would improve the economic viability of CCUS for emissions mitigation, particularly for coal-fired power. To date, the remarkable industrial experience achieved at the first generation of CCUS installations at coal-fired power stations has resulted in significant cost reductions.

In fact, CCUS for the coal-fired power sector is becoming cost-competitive with other emission reduction approaches. Real-world examples are provided to assist in the development of the appropriate policies and other drivers that are essential to moving CCUS forward at the required pace, including:

- **THE SASKPOWER BOUNDARY DAM CCS FACILITY** in Canada, the first large-scale, post-combustion CCUS installation at a coal-fired power station, began operation in 2014. At that time, it was estimated that cost savings of at least 30% for the construction and operation of the next similarly scaled CCUS facility could be achieved based on learning from commissioning and early operation.
- The **PETRA NOVA FACILITY** in Texas, United States, an industrial-scale CCUS installation at a coal-fired power station, began operation in 2017. It has also led to a greater understanding of, and confidence in, the main drivers of improved cost performance.
- The **2018 SHAND CCS FEASIBILITY STUDY** of a post-combustion CCUS retrofit at SaskPower's single-unit, 300 MW, coal-fired power station located near the Boundary Dam facility estimated that savings exceeding 60% per tonne of CO_2 captured could be realized for the next generation of CCUS operations. Herein, a consideration of the origin of these cost improvements is presented in terms of capital cost savings, operational cost savings, business case improvements, and finance/policy options.

Most large-scale CCUS installations to date have been undertaken in other sectors. It is essential to expand those opportunities, most urgently into the coal-fired power generation sector. Existing projects provide significant lessons for future CCUS design and development; many will lead to dramatic capital and operating cost reductions. Work to date has successfully demonstrated the favorable economics of size and other factors to reduce the cost of CO_2 capture. Technological advancements will lead to further cost improvements. Accordingly, promising new technologies, including membrane capture, oxyfuel combustion and BECCS have been highlighted herein. Continued progress in CCUS deployment will rely on the following:

- **IMPROVED UNDERSTANDING AND KNOWLEDGE.** Combining technical expertise to better understand the cost savings and design improvements for CO_2 capture must continue to facilitate progress.
- **REDUCED UNCERTAINTY ABOUT SHARED TRANSPORT AND STORAGE.** Facilitate necessary investment in the development of major infrastructure on transport and storage components, including better logistics planning.
- **STRENGTHENED POLICY AND FINANCIAL SUPPORT.** An international commitment must be made to establish supportive policy and innovative financing mechanisms to grow CCUS into a well-established industry.
- **CONTINUED INVESTMENT IN RESEARCH AND PILOT PROJECTS OF NEW TECHNOLOGIES, ALONG WITH COMMERCIAL CCUS DEPLOYMENTS.** The significant level of investment in research, piloting and demonstration over the past few decades must continue and, indeed, increase to help reduce investment risk associated with low emissions coal-fired power technologies. This will accelerate the technology development cycle. Research is also essential for independent and objective analysis, and generating data and developing expertise to accelerate design, permitting and operation of new coal power plants using specific black and brown coals in local conditions.

The application of CCUS in the power generation sector is the primary emphasis of this report. Globally, there will be over 20 commercial-scale CCUS projects in operation by 2020 with more than 37 Mt of anthropogenic CO_2 being captured and geologically stored annually. CCUS is not a new undertaking, yet it is rare in the coal-fired power sector with only two commercial CCUS installations in operation to date. Deep investment in CCUS needs to be made a high priority for G20 nations to reduce global energy-related emissions in order to honour the commitments in the Paris Agreement. Given the lack of available technology alternatives, many types of fossil fuel-based, emission-intensive processes will require CCUS to achieve the 2°C goal. CCUS is a key enabler to transition to renewable and alternative energy sources and an absolutely critical component for continued use of fossil energy where it makes economic sense. It will facilitate continued use of existing fossil-energy based infrastructure and industrial operations where we have no other current options, such as petrochemical production, in a carbon-constrained world.

Recently, welcome and encouraging improvement in the pace and progress of commercial CCUS projects, undertaken in conjunction with coal-fired power and related energy-based industries, has been realized. Learnings from implementing the first mover projects have resulted in cost saving strategies for subsequent projects. Notably,

> CCUS IN THE COAL POWER SECTOR IS ALREADY COST COMPETITIVE WITH OTHER FORMS OF EMISSION REDUCTIONS WHEN CONSIDERED IN TERMS OF COST PER TONNE OF CO_2 AVOIDED.

A clear and positive commitment to enhance knowledge, understanding, and critical know-how is apparent. This will inevitably lead to sustained improvement in the environmental performance of the coal power industry. Maintaining, or ideally increasing, momentum in commercial CCUS applications will make a meaningful contribution toward achieving the Paris Agreement's 2-Degree goal.

Carbon Capture Storage at a Glance

Accelerated CO_2 Emission Reduction

1	Source of carbon dioxide (CO_2) emissions from industrial or energy plants. With carbon capture and storage (CCS), large amounts of CO_2 will be captured, recycled and permanently stored.
2	Capture rates potentially exceeding 90% of the CO_2 in the flue gas, is captured and is then compressed into a dense phase liquid for easy transport.
3	The CO_2 is transported by pipeline. The CO_2 may also be transported by truck, rail or ship, depending on the needs specific to the region where the CCS project is located.
4	The CO_2 is sent deep underground for: **a** Use in Enhanced Oil Recovery (EOR) – where CO_2 is recycled and eventually permanently stored safely in depleted oil/gas formations. **b** Permanent storage into the microscopic spaces between grains in a porous reservoir rock formation – with depths exceeding 1km, and layers of dense impermeable "cap-rock" formations above it ensures that the CO_2 remains there indefinitely.
5	Measurement, Monitoring & Verification (MMV) - Rigorous and sensitive MMV equipment and procedures are put in place that can detect changes in CO_2 pressure and concentration in the subsurface to ensure the plume is growing within acceptable conformance limits and is staying within the injection formation permanently. As well, surface monitoring is completed regularly to ensure there is no CO_2 leakage into the atmosphere, groundwater, or soil, related to injection or surface CO_2 operations.

* The deep sandstone formation has microscopic spaces between its individual sand grains, or porosity, which allows it to hold high salinity water – that is 10 times more salty than the ocean. Due to the presence of this very salty brine, geologists refer to this type of formation as an aquifer.

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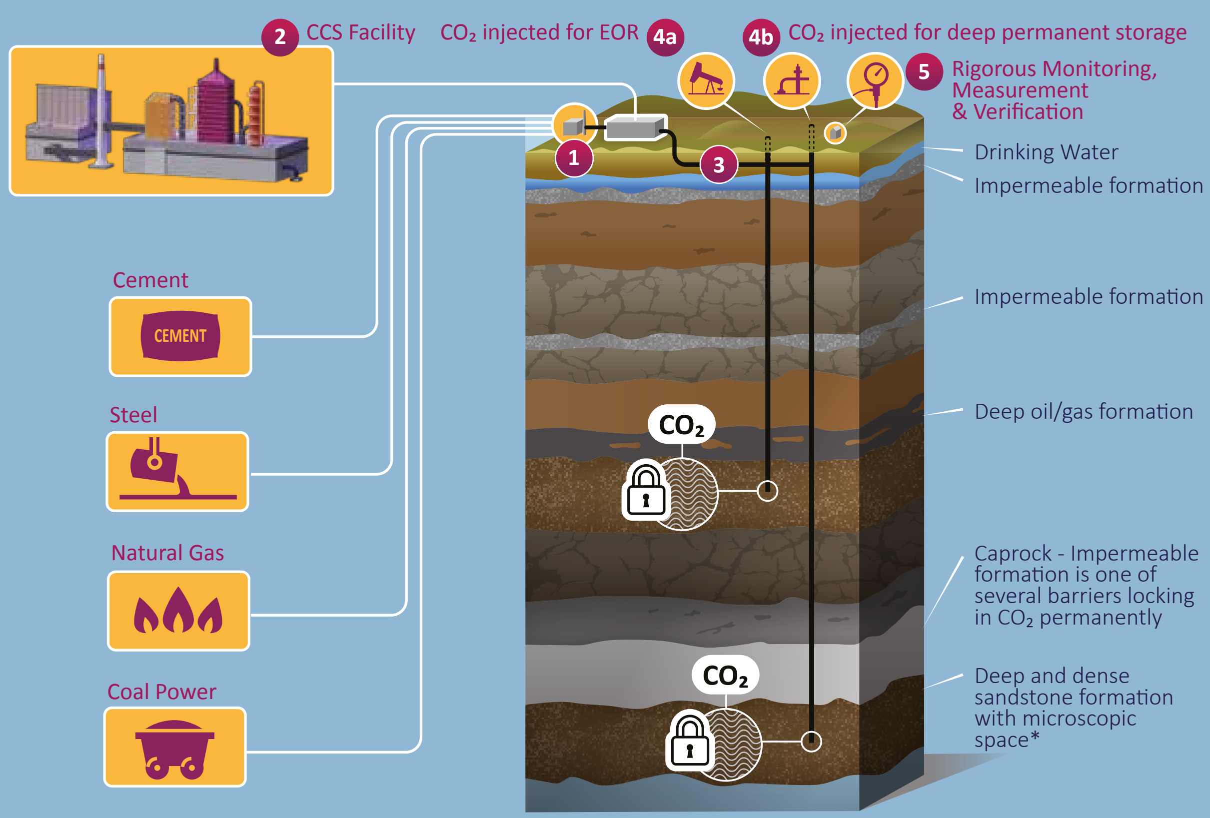

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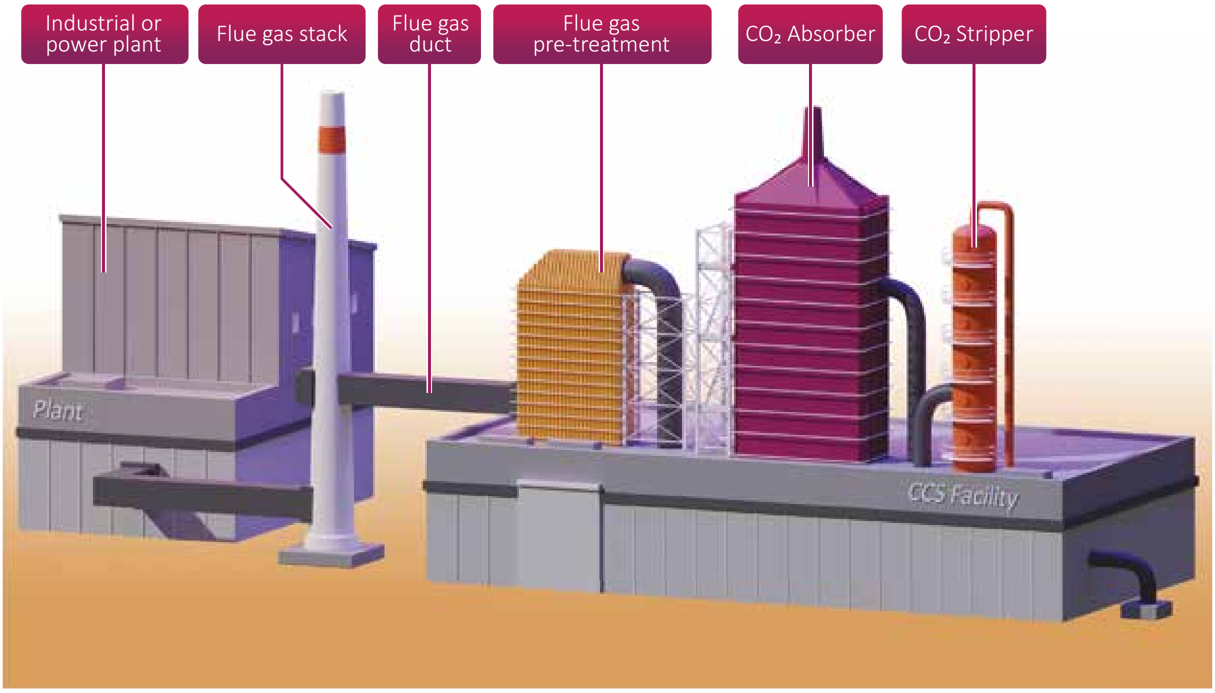
Numerous experts, affiliated with CIAB member companies and independent organizations, provided technical input and reviews of this paper.

The CIAB is a group of high-level executives from coal-related enterprises, established by the International Energy Agency Governing Board in July 1979 to provide advice to the IEA from an industry perspective on matters relating to coal. The views expressed are those of the CIAB. The sole purpose of this paper is to advise the IEA Secretariat in accordance with the role of CIAB. This paper draws on the experiences of CIAB members based on their involvement in the design, funding, construction, and operation of CCUS projects and energy infrastructure projects worldwide. This paper does not necessarily represent the views of IEA nor the acknowledged contributors.

Components of a carbon capture facility connected to an industrial power plant



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The Global Climate Imperative for CCUS

The Paris Agreement

The Paris Agreement on climate change was adopted by 197 governments at the 2015 United Nations Climate Change Conference (COP21) meeting in December 2015[1]. The Paris Agreement committed signatories to collectively, "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C…". The Agreement seeks to balance greenhouse gas (GHG) sources and sinks in the second half of this century, effectively requiring net-zero GHG emissions. Its goals are at significant risk without an international commitment to carbon capture, utilization and storage (CCUS)[2]. According to the Intergovernmental Panel on Climate Change (IPCC), achieving the 2°C goal is estimated to be more than twice as expensive without CCUS[3]. Reaching the 1.5°C aspiration would require net negative emissions on a massive scale that is only achievable through bio-energy CCUS (BECCS), Direct Air Capture (DAC) and bio-sequestration (e.g. afforestation).

Significant international progress in meeting such deep reductions in GHG emissions has not yet been made. Substantial carbon abatement must be undertaken in a manner that provides access to reliable and affordable energy, while supporting the economic development necessary to maintain and improve living standards, particularly in the developing world. Accelerated efforts to increase energy efficiency and deploy a portfolio of low-emissions energy and industrial technologies are also essential.

Implications from the International Energy Agency: The Need for CCUS

To meet the goals of the Paris Agreement, the pace and frequency of CCUS project implementation must rapidly increase in conjunction with commercial deployment of other clean energy technologies, including CCUS applied in the coal-fired power sector. This was made abundantly clear in the International Energy Agency's (IEA) World Energy Outlook (WEO) reports of 2017 and 2018[4,5]. WEO modeling makes it clear that coal will continue to meet between 12% and 22% of global energy demand to 2040.

Low-cost, reliable energy from coal-fired power stations will remain in high demand, particularly in developing countries. Growing energy needs in these nations will lead to continued use of the existing generation fleet and likely necessitate construction of new generation facilities. Over a third of the existing global coal-fired power fleet is less than 10 years old. Given the scale of financial capital already deployed, it is unrealistic to expect this fleet to be prematurely shut down.

Consequently, significant growth in the installation of CCUS at existing and new coal-fired power generation facilities will be critical to meeting the 2°C goal and is the central focus of this report.

1 United Nations Framework Convention on Climate Change. Paris Agreement. COP 21 Meeting. December, 2015. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

2 For the purposes of this paper, CCUS is used to collectively refer to projects that utilize CO_2 to generate revenue, such as enhanced oil recovery (EOR), as well as projects that utilize dedicated geological storage of CO_2.

3 IPCC (Intergovernmental Panel on Climate Change). Climate Change 2014 Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. UK: Cambridge University Press, 2014. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf .

4 International Energy Agency. World Energy Outlook 2017 (WEO-2017). Paris: IEA, 2017. https://www.iea.org/weo2017/.

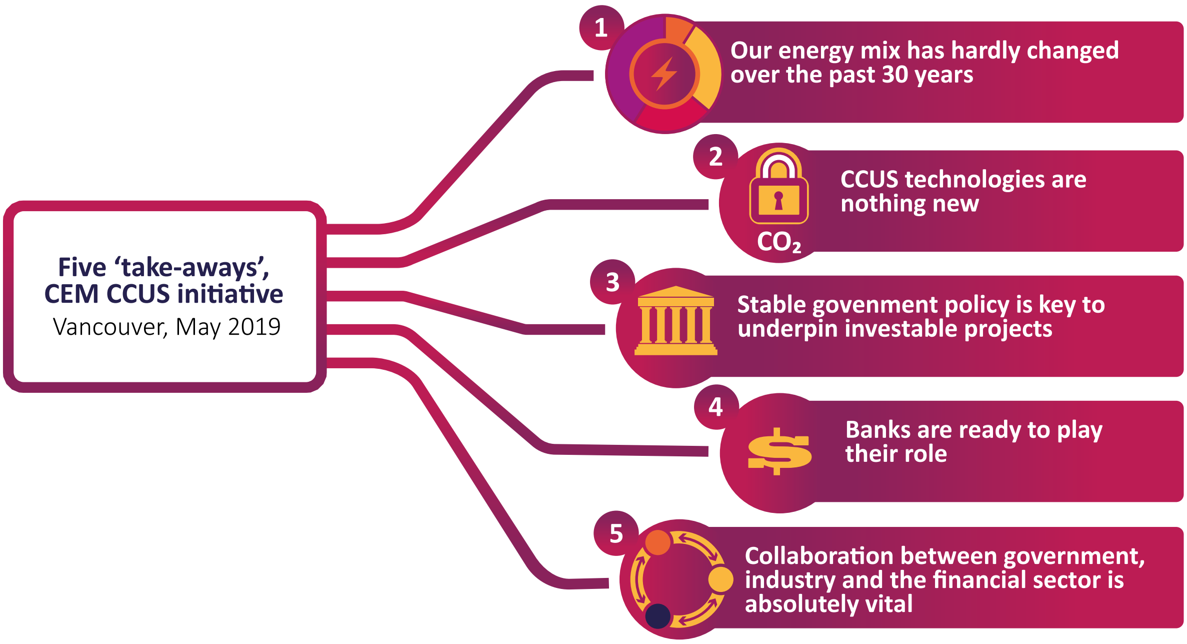
5 International Energy Agency. World Energy Outlook 2018 (WEO-2018). Paris: IEA, 2018. https://www.iea.org/weo2018/.

In 2012, the IEA estimated that 12 GW of CCUS-enabled power plants will be required by 2020, 215 GW by 2030, and 664 GW by 2050 to remain on a pathway to achieving the 2°C goal[6]. However, since there are only a handful of projects in the planning phase, not a single new CCUS-enabled power plant under construction as of 2019, and only the two existing plants operating in North America, it would be impossible to achieve the first target even by 2024. Accordingly, the need to deploy CCUS retrofits at coal-fired power stations becomes more pressing. Furthermore, attaining the even more ambitious goal of limiting climate change to well below 2°C will require a substantial increase in efforts toward even higher rates of CCUS deployment, along with renewable and alternative energy power installations. Rapid growth in the use of CCUS with bioenergy (BECCS) and other applications will also be essential to help achieve the targeted CO_2 emission reductions.

An International Commitment to CCUS

At the present time, international commitment to CCUS is disjointed. Some governments meet under the new Clean Energy Ministerial (CEM) CCUS Initiative[7] (*see Figure 3*) or the long-standing Carbon Sequestration Leadership Forum[8], while the alignment of various companies and organizations has formed initiatives such as the Oil and Gas Climate Initiative[9], the Carbon Capture Coalition[10] and the Carbon Utilization Research Council[11] in the United States. Central to these efforts is a shared mandate for the development of CCUS. The United States has improved the economics for CCUS with recent positive changes to the 45Q tax credit that has led to strong bipartisan support for CCUS. However, there is no international concerted force to enable incentives and funding that would support a more rapid uptake of the technology.

Figure 3: *Key Messages from Clean Energy Ministerial CCUS Initiative Side-Event, "Accelerating CCUS Together – Financing a Key Piece of the Clean Energy Puzzle" (2019)*



6 International Energy Agency. Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation. Paris: IEA, 2012. https://webstore.iea.org/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation.
7 Clean Energy Ministerial CCUS Initiative. 2019. http://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/carbon-captureutilization-and-storage-ccus-initiative
8 Carbon Sequestration Leadership Forum (CSLF). 2019. https://www.cslforum.org/cslf/
9 Oil and Gas Climate Initiative. 2019. https://oilandgasclimateinitiative.com/
10 Carbon Capture Coalition. 2019. http ://carboncapturecoalition.org/
11 Carbon Utilization Research Council. 2019. http://curc.net/

CCUS technology can be deployed at the appropriate rate and scale to facilitate achieving the goals of the Paris Agreement. This will necessitate incentives and support by meaningful public policies that enable a deployment trajectory consistent with the 2°C goal. Robust, well-designed policies must be enacted with urgency to drive meaningful action.

THE SAME PUBLIC POLICY SUPPORT AND POLITICAL COMMITMENT THAT EXISTS FOR OTHER LOW-CARBON ENERGY TECHNOLOGIES DOES NOT EXIST FOR CCUS.

Government coordination with industry to enact well-designed policies would remove barriers inhibiting both public and private banks from financing well-designed CCUS projects, thereby enabling CCUS project deployment at the necessary pace to make meaningful global GHG emission reductions.

Experience from First-Generation CCUS Projects at Coal-Fired Power Stations

Advancing Toward Success

While CCUS is already a cost-effective technology to mitigate emissions, the costs for specific CCUS coal-fired power sector projects can be reduced to levels far lower than previously expected. A deeper understanding of the various costs related to CCUS and the associated drivers for their reduction will provide policymakers and the finance community with greater confidence in the potential for CCUS to deliver necessary GHG emissions reductions.

Current carbon capture technology is based on the natural gas sweetening process developed by R.R. Bottoms in the 1930s[12]. Recent innovative changes to the basic process have been developed and deployed globally at industrial and coal-fueled power facilities.

While the use of CCUS outside natural gas processing has generally been in first-of-a-kind or high-value niche applications, the technical viability of carbon capture technology has been clearly demonstrated. Furthermore, following several decades of experience from industrial-scale CO_2 enhanced oil recovery (EOR) operations, the CO_2 transport industry is mature. The ability to safely store CO_2 in the subsurface has also been proven where suitable geology exists, and essential operating and monitoring practices are implemented. These key factors validate the first generation of CCUS technology as a proven technology. However, as with any new technology, significant progress and associated capital and operating cost reductions will be afforded by further innovation resulting from commercial-scale implementation over the coming years.

The two first-generation, industrial-scale, post-combustion CCUS installations on coal fired power stations provided the practical experience, learning and knowledge from which conclusions are being drawn concerning capital and operating cost reductions. These operations are:

- **SaskPower's Boundary Dam Unit 3 CCS Facility (BD3)**, a commercial CCUS installation at a coal-fired power station that began operation in October 2014; and
- **NRG's Petra Nova Facility**, a larger, CCUS installation at a coal-fired power station that began commercial operation in 2017.

Demonstrating CCUS at Coal-Fired Power Generation Facilities

SaskPower's Boundary Dam Unit 3 CCS Facility

The BD3 project in Saskatchewan, Canada, pioneered large-scale CO_2 capture for power generation as the world's first fully-integrated CCUS facility at a coal-fired power station[13]. The nominal capture rate of the facility is 1 million tonnes (Mt) of CO_2 per year. The BD3 facility includes CO_2 capture, compression, and transport. The BD3 capture facility is fully integrated with its host power plant from which it draws its steam and power needs. CO_2 produced at the BD3 operation is utilized for nearby enhanced oil recovery (EOR) operations, while also providing CO_2 for injection and permanent geological storage at Aquistore, an onsite CO_2 measurement, monitoring and verification (MMV) project, at a depth of 3,400 m in a deep saline aquifer.

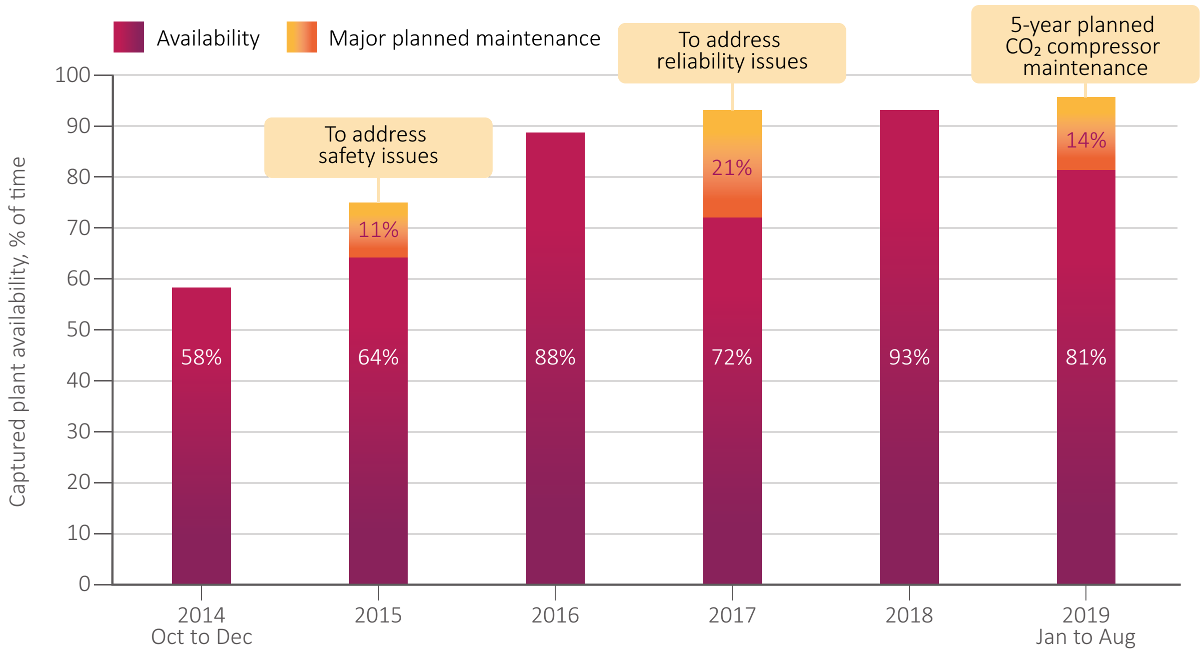
12 Kohl, A. and Nielsen, R. Gas Purification (5th Edition). USA: Gulf Professional Publishing, 1997.

13 Preston, C.K. The Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station. IEA Greenhouse Gas R&D Programme (IEAGHG) Technical Report 2015-06. UK: IEAGHG, 2015. https://ieaghg.org/publications/technical-reports.

Aerial View of the BD3 Capture Facility at the SaskPower Boundary Dam Power Station located near Estevan Saskatchewan *(Courtesy: International CCS Knowledge Centre).*

The CCUS story at BD3 is one of significant progress and inspiration for future CCUS projects. This successful installation has paved the way for significant capital and operating cost reductions paired with increased efficiencies to further improve the next generation of CCUS installations. Furthermore, in 2019, the facility celebrated a significant milestone – a cumulative total of three million tonnes of CO_2 captured and injected since startup. With stable operation achieved (*see Figures 4 and 5*), the next focus for BD3 has become improving the efficiency of the operation and reducing costs.

Figure 4: *Performance of the BD3 Carbon Capture Facility: Reliability Based on Annual Availability of the Capture Facility from Startup in October 2014 through July 2019*

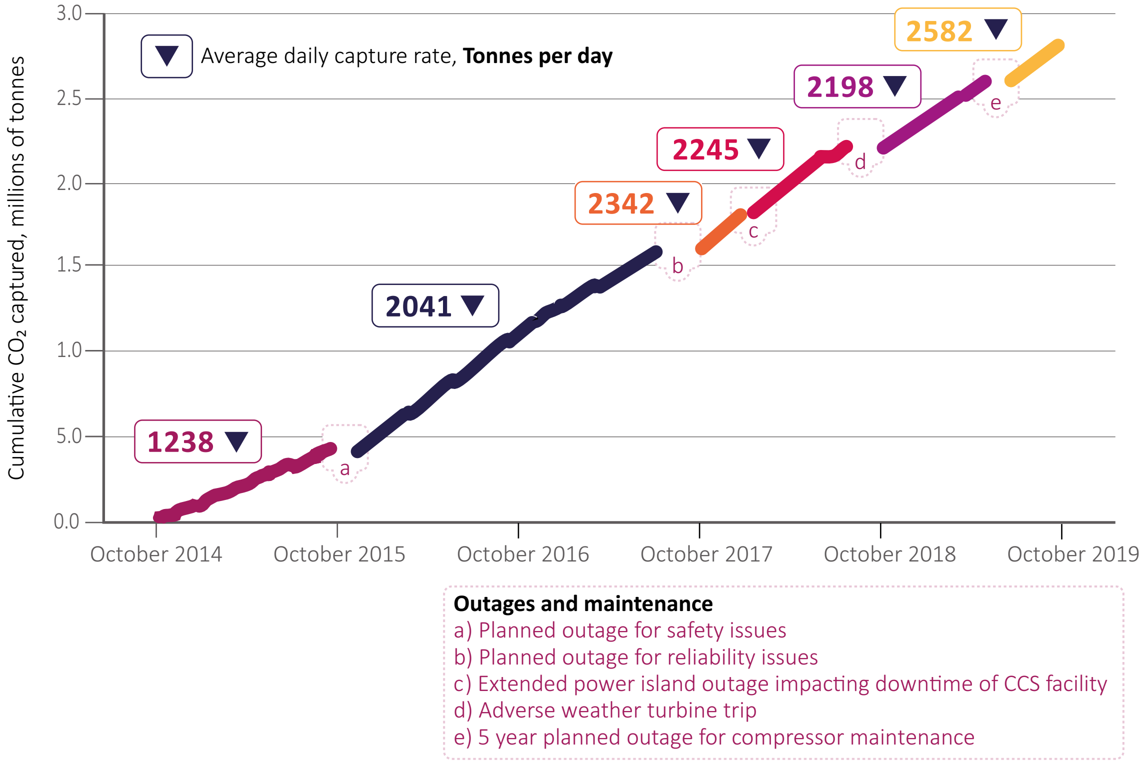


Capture plant availability is the percentage of time the capture plant is capturing CO_2 while the power plant is operating at least 50% load. Plant load at 50% was the original anticipated minimum load for operation of the capture system.

The calculations include both the original planned maintenance durations as well as any unplanned extensions.

Source: International CCS Knowledge Centre

Figure 5: *Performance of the BD3 Carbon Capture Facility: Cumulative CO_2 Captured from Startup in October 2014 through 2019*



Source: International CCS Knowledge Centre

The practical learning from the hands-on experience of BD3 continues to be shared by the International CCS Knowledge Centre. Its primary role is to provide experience-based guidance to assist in significantly reducing the risks and costs of future CCUS facilities[14].

NRG's Petra Nova Facility

Carbon Capture Facility at Petra Nova WAParish Station, *(Courtesy: NRG Energy).*

14 International CCUS Knowledge Centre. 2019. https://www.CCUSknowledge.com

In early 2017, the Petra Nova Facility in Texas, United States began full-scale operation. Its nominal capture rate is 1.4 Mt per year of CO_2 that is pipelined for storage through EOR at an oil field 130 km from the coal-fired power station that is located in Parish County[15].

Similar to BD3, the Petra Nova capture plant uses a proprietary amine solvent to remove CO_2 from the flue gas of the coal-fired power plant host. However, Petra Nova captures CO_2 from a slip stream of the flue gas previously vented to the atmosphere rather than the entire amount, and uses a purpose-built, gas-fired turbine to generate the required steam and power for the capture process, rather than drawing energy from the host power plant[16] as is done at BD3.

The project engaged an industry partner approach to directly produce and sell oil from CO_2 injection rather than selling CO_2 to an oil operator, which increases the project risk profile, and the potential returns. All of the CO_2 captured at Petra Nova is utilized for EOR.

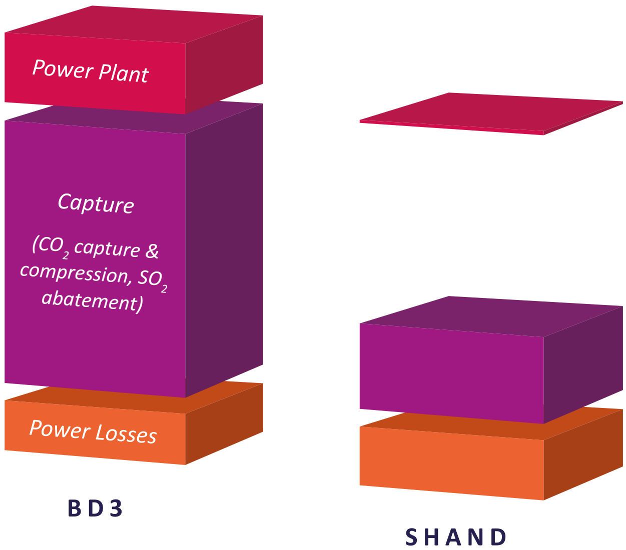
15 US Department of Energy. Office of Scientific and Technical Information (OSTI). W.A. Parish Post-Combustion CO2 Capture and Sequestration Project Final Public Design Report. Report No. DOE-PNPH-0003311-2. February 2017. www.osti.gov/servlets/purl/1344080.

16 Patel, S. Capturing Carbon and Seizing Innovation: Petra Nova is POWER's Plant of the Year. Power Magazine. August 2017. www.powermag.com/capturing-carbon-and-seizing-innovation-petra-nova-is-powers-plant-of-the-year/?pagenum=5.

Driving Down the Cost of CCUS

In recent years, numerous studies and associated research have considered the anticipated cost savings of CCUS[17,18] based on the significant knowledge that has been developed from CCUS projects conducted to date. For instance, it is generally accepted that the primary driver for achieving significant cost reductions is to deploy CCUS at scale[19]. While early cost reduction strategies were based on incremental improvements achieved by pilot and research projects, there is now a growing depth of practical understanding based on commercial-scale deployment to better evaluate cost-reduction potential to improve performance at future CCUS facilities. Nonetheless, continued pilot and research projects are advancing knowledge about the potential for innovating existing technologies and furthering the development of new technologies.

Figure 6: *First-Generation CCUS (BD3 Facility) Compared with Second-Generation CCUS (Shand Feasibility Study) Shows a 67% Reduction in Capture Plant Capital Costs*



Source: The Shand CCS Feasibility Study[20]

Industrial technological progress is characterized by efficiency improvements and capital and operating cost reductions based on lessons learned at early operations that are used to improve the designs and operating practices at subsequent generations of facilities. First-generation projects often have anticipated savings of around 20-30% should they be repeated using the expertise and educated hindsight gained from early operation. A recent feasibility study for CCUS retrofitting undertaken by the International CCS Knowledge Centre for the SaskPower Shand Power Station demonstrated that applying knowledge from BD3 at a larger scale could achieve a reduction of up to 67% in capital costs on a per tonne of CO_2 captured basis[20] (*see Figure 6*). Furthermore, the cost of CCUS would likely decline with deployment of future technology generations.

While a retrofitted CCUS facility cannot be precisely duplicated, understanding commonalities with previously deployed CCUS facilities may guide development considerations. The principal

17 UK CCS Cost Reduction Task Force. Final report. The potential for reducing the costs of CCS in the UK. May 2013. https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report.

18 UK CCUS Cost Challenge Taskforce. Delivering clean growth: CCUS Cost Challenge Taskforce report. July 2018. https://www.gov.uk/government/publications/delivering-clean-growth-ccus-cost-challenge-taskforce-report.

19 MacDowell N., Fennell, P.S., Shah, N., and Maitland, G.C. The role of CO_2 capture and utilization in mitigating climate change. Nature Climate Change. 2017. 7, 243-249. https://www.nature.com/articles/nclimate3231 .

20 International CCUS Knowledge Centre. The Shand CCS Feasibility Study Public Report. November, 2018. https://CCUSknowledge.com/pub/documents/publications/.Shand%20CCUS%20Feasibility%20Study%20Public%20Report_NOV2018.pdf

considerations in the Shand Feasibility Study included location, availability of space, and steam cycle design of the facility. Additional factors such as scale, modularization, simplifications and other lessons learned from BD3 directly contributed to estimated cost reductions.

A CCUS project will only proceed with adequate financing and policy support, which is facilitated by a compelling business case that could include such benefits as leveraging existing and common infrastructure, appropriately valuing the contribution of dispatchable power to the power system, and reduced capital and operating costs. The balance of this report summarizes key drivers that are likely to enhance the deployment of CCUS projects in the coal power sector.

Capital Cost Reduction

Capital costs of the carbon capture facility accounted for more than half of the total cost of capture at first-generation, CCUS retrofits at coal-fired power plants. Applying the experience gained from the design and operation of these facilities will directly contribute to improving the economics of future CCUS installations deployed by the coal power industry.

Scaling Up the CCUS Plant

Economies of scale are fundamental drivers in the utility industry. Larger facilities are typically more economically efficient that their smaller counterparts. The original BD3 coal fired power unit was rated at 150 MW (gross) prior to its retrofit, which was appropriately sized for its regional grid demand requirements. However, the unit is small by global standards. The largest existing coal-fired power units are typically rated at 1100 MW or more with a much higher CO_2 emission reduction potential. The Shand Feasibility Study was conducted to support the design of a second-generation CCUS facility at a 300 MW coal fired unit with a proposed annual capture capacity of more than 2 Mt per year, twice the capacity of the BD3 capture plant. The Shand Feasibility Study demonstrated that significant cost reductions could be achieved on a per unit of CO_2 capture basis due to the larger scale of the power unit.

The level of emissions from a power plant is a function of both its generating capacity and its efficiency, which directly impact the size of its associated capture facility. Larger units typically generate more emissions. Increasing the capture capacity two-fold will not necessarily result in doubling the costs for the capture facility due to economies of scale. The Shand Feasibility Study demonstrated that increased overall capture capacity, combined with marginal increases in cost for the capture facility, could result in a reduced cost of capture.

Site Layout and Modularization

The layout and availability of space of a new CCUS facility are important design considerations since a minimal footprint reduces capital costs. Failure to site the capture facility in close proximity to the power unit would increase the length of interconnections, leading to increased material costs and increased facility integration complexity with an associated reduction in operational efficiency. The Shand site was originally designed to host a second power unit that was not constructed. This resulted in minimal site congestion (*see Figure 7*). Employing this siting strategy enabled early design concepts to optimally place energy-intensive process units alongside the power plant. Ideal locations for the CO_2 absorber tower beside the boiler house, the CO_2 desorber alongside the boiler house / turbine house wall, and the CO_2 compressor beside the power generator were possible. This alignment minimized the length of interconnections for flue gas ducting, steam piping, and electrical connections, thereby significantly reducing material costs. Additionally, conjoining the two plants could reduce personnel access costs by enabling shared elevators and stairwells. The BD3 and the

Petra Nova projects have more densely-developed sites that complicated the siting of their capture facilities, resulting in increased costs and fewer opportunities for performance enhancement.

Figure 7: *Conceptual Diagram of Shand Power Station with a Carbon Capture Facility*

Source: The Shand CCS Feasibility Study[20]

Modular construction for major infrastructure projects has been widely embraced by industry as an effective means to control labour and material costs. While modularization may not always be possible, assembly of structural steel, equipment, piping, electrical and instrumentation offsite has been shown to dramatically increase productivity, reduce travel costs, and result in shorter on-site construction time. This approach also provides access to lower-cost labour pools globally, while assuring that standards are met at reduced cost and fewer power plant site disturbances are experienced.

Increasing Capture Capacity

The percentage of CO_2 capture at a CCUS facility is the amount of CO_2 that is separated or removed by the capture process from the total CO_2 in the flue gas stream. Post-combustion capture is often targeted at a 90% capture rate; however, some facilities may choose a lower capture rate simply to meet regulatory or other requirements. When it was approved for construction, jurisdictional GHG emissions regulations applicable to the BD3 facility were anticipated but were uncertain. The decision to select a 90% design capture rate at BD3 was based on the best technically-achievable emissions reduction and the belief that this should meet forthcoming regulations.

The BD3 Carbon Capture Facility located at the SaskPower Boundary Dam Power Station near Estevan Saskatchewan *(Courtesy: International CCS Knowledge Centre).*

A recent study has shown that capturing less than 90% of the CO_2 in a flue-gas emission stream would likely increase the cost of capture on a per tonne basis for the most advanced technologies[21]. Furthermore, a sensitivity study of the proposed Shand CCUS design showed that a 95% capture rate improved costs compared with a 90% capture rate. Research on post-combustion capture has suggested that increased capture rates above 90% are cost effective and contribute to cost reductions[22]. As the flue gas moves up through the absorber tower CO_2 molecules are removed from the flue gas by the absorbent. Flue gas CO_2 concentration is the lowest at the top of the absorber column.. A tipping point exists beyond which it becomes increasingly difficult for the absorbent to react with reduced levels of CO_2 in the flue gas. Beyond this point, the economics of the capture facility degrade due to the excessive additional costs that would be incurred to capture the remainder of CO_2 (i.e. costs that are related to increased height of the column and/or increased the surface area inside the column). Research is underway to more accurately identify the associated tipping point for setting the target capture rate for a given facility.

21 International CCUS Knowledge Centre. "Summary for Decision Makers on Second Generation CCUS Based on The Shand CCS Feasibility Study". 2018 . https://CCUSknowledge.com/pub/documents/publications/Summary%20for%20Decision%20Makers%20on%20Second%20Generation.pdf

22 Ferron, P., Cousins, A., Jiang, K., Zhai, R., Hia, S.S., Thiruvenkatachari, R., and Burnard, K. Towards Zero Emissions from Fossil Fuel Power Stations. International Journal of Greenhouse Gas Control. 2019. 87, 188-202.

Increased Efficiency of the Host Power Unit

Thermal power plants have a wide range of emission intensities associated with their type, age, and efficiency. For example, coal-fired power plants installed with older technologies typically operate at lower main steam pressure and temperature, as governed by the limitations of the materials and technology economically available at the time of their initial design. Typical emission intensities of these older units can be in excess of 1,200 tCO_2/GWh. The Shand power station is a subcritical, lignite-fired unit with an emission intensity of approximately 1,100 tCO_2/GWh. A modern, advanced, ultra-supercritical plant, generally referred to as high efficiency, low emission, or HELE, may have an emission rate as low as 670 tCO_2/GWh[23]. The approximately one-third reduction in emissions intensity between old and new coal power units has a direct impact on the required size of the capture plant. This reduces the parasitic power losses and capital costs of the CCUS retrofitted facility.

Optimizing the CCUS Operating Envelope

The requirements for reliability and capability of a thermal power plant's operating envelope are quite different from the requirements for its associated carbon capture plant. A thermal power plant must maintain its capability to supply power at high reliability and high capacity over a wide range of operating conditions, such as weather extremes, fuel quality variations, and equipment issues.

Although long-term capture at high levels of availability is the operating goal of the capture facility, the ability to curtail CO_2 capture, either fully or partially at any given point in time, is desirable and may contribute to significant cost savings. Sizing of the capture facility's cooling system is a useful example to consider[19]. Instead of designing the cooling system to meet requirements from the hottest to the coldest days of the year, a narrower range of ambient temperature could favour a smaller system size with associated cost savings. Utilizing this design strategy, CO_2 capture could be curtailed to manage periods of insufficient cooling capacity. The overall net impact on annual capture volume may be viewed as acceptable given the advantage afforded by the associated capital cost savings.

A thermal power plant that is capable of supplying power at variable loads, as dictated by regional grid supply and demand, is highly valuable. The ability of the capture facility to follow the variability of the thermal power plant, while continuing to capture CO_2 at full capacity, is key to overall emission reductions. As thermal power generation stations reduce output, their efficiency decreases, thereby resulting in increased CO_2 emission intensities. The ability to maintain capture facility operations under these conditions would reduce the emissions impact of variable loads, while decreasing flue gas volumes. A capture facility is typically designed based on full-load flue gas volumes. Consequently, at reduced loads the capture facility would be able to capture CO_2 at increased overall rates.

Development of a CCUS Supply Chain

Well-developed supply chains increase competition, spur innovation and reduce technology costs, ultimately having a positive impact on capital costs. Development of a CCUS supply chain would depend upon establishing a favorable landscape for a CO_2 market under which suppliers would have the confidence in the installation of numerous future CCUS projects to facilitate the growth of the supply chain.

23 Minerals Council of Australia, New Generation Coal Technology – Why HELE coal-fired power generation is a part of Australia's energy Solution. February 2017. http://www.newhopegroup.com.au/files/files/Why%20HELE%20is%20part%20of%20Australia%20s%20energy%20solution%20-%207%20February%202017.pdf

Characteristics of a well-developed supply chain include:

- Supply of all equipment, such as packing, heat exchangers, compressors, and related raw materials that would be available within reasonable timeframes to meet demand;
- Suitable competition between equipment suppliers that would exist to drive efficiency, innovation and ultimately to lower costs; and
- Standardization and significant volumes of supplier orders that would enable expansion by manufacturers toward efficient scales of production.

The Carbon Capture Facility at the Petra Nova WA Parish Power Station *(Courtesy: NRG Energy).*

Operating Cost Reduction

CCUS-enabled coal-fired power plants generally operate at higher cost than conventional thermal power stations for several reasons. First, additional energy is required to operate the capture and compression systems which reduces the net energy output of the power plant in the case of a fully integrated design, such as BD3, or incurs additional operating costs if a separate external energy supply source is installed, as in the case of Petra Nova. Second, further operating expenses are incurred due to consumption of solvents, chemical reagents, catalysts and disposal of waste products. Finally, additional staff is required to operate and maintain the capture facility. The first generation of CCUS plants has provided concrete understanding about real-world operations. Early challenges faced by these facilities have highlighted the areas where the biggest gains could be made to reduce operating costs.

Amine Degradation

Solvents typically used by existing post-combustion capture plants are amine based that selectively bond with CO_2 at cold temperatures and release pure CO_2 upon heating. The solvent is continually circulated, repeatedly capturing and releasing CO_2. The amine molecules tend to break down or degrade during prolonged use, eroding capture efficiency and necessitating its removal and replacement with fresh solvent. The cost to replace degraded amine has a significant operational cost impact[24] and represents a fundamental operational risk characteristic of amine-based capture systems. Extensive piloting using identical flue gas and solvent combinations to quantify the risks of amine degradation is considered a standard practice for appropriate CCUS facility design[25,26,27,28] to determine anticipated costs for amine maintenance when developing the business case for a CCUS project. Unfortunately, this risk mitigation strategy increases the cost of development and the timeframe for CCUS deployment, which has resulted in significant levels of industry-driven research directed toward identifying sources of accelerated amine degradation and potential mitigation strategies[29]. Technology providers have focused on the reduction of the impact of amine degradation and the associated costs for managing amine quality. However, additional work must be undertaken by projects at industrial-scale facilities to ensure associated cost reductions.

The Carbon Capture Test Facility located at the SaskPower Shand Power Station near Estevan, Saskatchewan *(Courtesy: SaskPower)*

24 Langenegger, S. "SaskPower spending more to capture carbon than expected". CBC News. December 14, 2016. https://www.cbc.ca/news/canada/saskatchewan/saskpower-carbon-capture-1.3896487

25 Gorset, O., Knudsen, J.N., Bade, O.M. and Askestad, I. Results from testing of Aker Solutions advanced amine solvents at CO_2 Technology Centre Mongstad. Energy Procedia. 2014. 63, 6267 – 6280.

26 Wilson, M., Tontiwachwuthikul, P., Chakma, A., Idem, R., Veawab, A., Aroonwilas, A., Gelowitz D., Barrie, J. and Mariz, C. Test results from a CO_2 extraction pilot plant at Boundary Dam coal-fired power station. Energy. 2004. 29, 1259-1267.

27 Hirata, T., Nagayasu, H., Yonekawa, T., Inui, M., Kamijo, T., Kubota, Y., Tsujiuchi, T., and Shimada, D. Current Status of MHI CO_2 Capture Plant technology, 500 TPD CCUS Demonstration of Test Results and Reliable Technologies Applied to Coal Fired Flue Gas. Energy Procedia. 2014. 63, 6120 – 6128.

28 Wilson, M., Tontiwachwuthikul, P., Chakma, A., Idem, R., Veawab, A., Aroonwilas, A., Gelowitz D., Barrie, J. and Mariz, C. Test results from a CO_2 extraction pilot plant at Boundary Dam Coal-fired Power Station. Energy. 2004. 29, 1259-1267.

29 Knudsen, J.N., Wærnes, O., Svendsen, H.F. and Graff, O. Highlights and main findings from the 8-year SOLVit R&D programme – Bringing solvents and technology from laboratory to industry. 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

Maintenance Costs

First-generation CCUS facilities were built without the benefit of operational experience. Consequently, the maintenance requirements of the facility were not factored into design. A deeper understanding of the impact of maintenance on the design and operating cost of the newer facilities has been developed, based on actual operations, along with effective strategies to optimize operating equipment.

Maintenance costs are normally kept under tight control with advance planning. Emergency maintenance work carries a premium that may be many times higher than the cost of planned maintenance. Unplanned work often results in the need for CCUS plant shutdown with the associated reduction in overall capture rate. To avoid this, redundancy may be deployed at key pieces of equipment, such as key heat exchangers, to improve the operational reliability of the facility. This approach enables continued regular operations using the duplicate equipment while in-situ maintenance is performed on the affected equipment by existing plant staff during normal work hours rather than an emergency dispatch team, thereby significantly reducing CCUS facility operating costs.

Inside the BD3 Power Generator during scheduled maintenance *(Courtesy: International CCS Knowledge Centre).*

Optimization of Thermal Energy

Energy required to operate the CO_2 capture process includes: 1) thermal energy for solvent regeneration to release CO_2, and 2) electrical energy for CO_2 compression. A fully integrated capture facility draws its energy needs from the host power plant, as in the case of BD3. Alternatively, a purpose-built auxiliary power plant may be constructed to service the capture facility, which was deployed at Petra Nova.

One of the key challenges encountered by a fully integrated, post-combustion capture operation is minimizing the impacts of the capture facility's energy requirements on the host power facility. Sourcing energy for capture from the power plant imposes a power production penalty or "parasitic load" that reduces plant's net power output. The amount and the source of the required thermal energy are critical to the operational efficiency and flexibility of the power plant. A considerable amount of research and technological development has minimized the energy requirements of the CO_2 capture process, leading to commercial proprietary solvents, such as those used at BD3 and Petra Nova, that offer performance advantages reducing energy needs by as much as 30% compared to conventional amines.

The source of thermal energy has an impact on the overall capture costs. A comparison of BD3 and Petra Nova is useful to consider. If steam is extracted from the host thermal power plant, as in the case of BD3, the generation capacity of the unit decreases. Additionally, portions of the steam turbine may be replaced to optimize the steam extraction pressure without imposing throttling losses to enable provision of peak efficiency at full load[20]. Furthermore, the quantity of steam available, although not linearly related, will generally follow the demand of the CO_2 capture facility.

The kettle reboiler inside the Carbon Capture Test Facility at the SaskPower Shand Power Station *(Courtesy: SaskPower)*

In the case of Petra Nova, where an auxiliary, cogeneration, natural gas turbine supplies steam for CO_2 capture, it may be difficult to dispatch the two power units independently. Furthermore, a guarantee to meet demand from the grid for the new gas turbine cannot be made without compromising efficiency as the coal-fired power plant reduces its load to respond to daily dispatch variations. A benefit of this arrangement is that the lack of work in the power plant reduces down time of the host facility, and decreases the likelihood that the project will require the environmental permit to be updated.

The conclusion that may be drawn from this comparison is that extracting steam from the existing power plant would have the lowest impact and provide the most flexible and economic option for new CCUS facilities[20], however impacts on unit environmental permitting may need to be considered.

Water Consumption

Most commercial operations consider the environmental and cost impacts of water supply and use. A thermal power plant is sited accordingly. Lack of appropriate water supply may limit or halt expansion at a given site, and most power plant sites have been developed to the point that no additional water is available for cooling purposes. A CCUS system may be designed without the need for additional water to support the cooling requirements of the facility by sourcing it from flue gas condensation using a combination of dry and wet cooling[20]. This purposeful reuse of water reduces the volume of process waste from the power plant site, thereby decreasing associated treatment and disposal costs. This cost-saving opportunity is higher at power plants burning high-moisture fuels.

The evaporative cooling towers at the SaskPower Shand Power Station *(Courtesy: SaskPower).*

Compression Efficiency

CO_2 compression requires energy that imposes a substantial load on the power plant. Compression power at BD3 accounts for more than a third of the lost electricity output associated with the CCUS facility. The CO_2 capture plants at BD3 and Petra Nova were optimized for full load operation, and each employ a single, integrally-geared, CO_2 compressor that realizes the best efficiency at full load and has limited ability to accommodate lower flows of CO_2 without incurring significant efficiency losses. Compressor design improvements are required to maintain efficiency and operational flexibility to improve load following capability at the CCUS facility.

Digitalization

Digitalization can improve safety, increase productivity, and reduce costs in the coal and power industries. The potential impact and the associated barriers of these improvements varies considerably. However, overall savings could amount to 5% of the total annual power generation costs.

Digital data and analytical modeling could help achieve greater efficiencies and reduce power system operation and maintenance costs in several ways:

- Improved planning by reducing outages through better monitoring and predictive maintenance and limiting downtime by rapidly identifying points of failure,
- Improved efficiency of combustion in power plants that would lower loss rates in networks,
- Improved project design across the overall power system,
- Extend the operational lifetime of assets, and
- Increase the resilience and reliability of power supply.

CO_2 Transport and Storage Cost Reduction

The development of new CO_2 storage locations incurs significant costs. Additional costs, though comparatively lower, may be incurred due to enhanced requirements for monitoring as higher volumes of CO_2 are injected at established storage sites.

The UK CCS Cost Reduction Task Force[30] has estimated that *storage* costs for CCUS-equipped power plants may be reduced from £25/MWh for early CCUS projects to £5-10/MWh through investment in a CO_2 hub or common storage site with a capacity of up to 5 Mt of CO_2 per year. Should a storage cluster be developed to utilize several storage types and geologies, the reliability of CO_2 storage would increase, thereby reducing development risk. This approach will be vital to assure economically-scaled CCUS-enabled fossil-fired power generation projects can be delivered and financed at costs in line with industry norms.

Pipeline construction and installation costs increase at lower rates with increasing CO_2 transport capacity. This is due to the economies of scale achieved as the volume of transported gas grows. Consequently, with appropriate advance planning for surplus capacity, there is significant potential to decrease the cost of transporting CO_2 at higher volumes. Other fundamental drivers of transport costs include pipeline distance; crossing terrain, particularly onshore; and planning costs. Considering these variables, the lowest cost transport network would:

- Transport large volumes of CO_2 in appropriately-sized pipelines;
- Consider the sizing of trunk-line sections and feeder-line sections to ensure high utilization over the longest period of the asset lifetime;
- Minimize CO_2 transportation by accounting for terrain, shoreline crossings and planning constraints; and
- Minimize the need for constructing additional pipelines that would incur significant planning costs.

30 UK CCS Cost Reduction Taskforce. CCS Cost Reduction Task Force: Final Report. May 2013. https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report. [Costs quoted in 2012 British Pounds Sterling (£)].

The Task Force has anticipated that *transport* costs for CCUS-enabled power plants could drop from £21/MWh for early pipeline projects carrying 1-2 Mt CO_2 per year to £5-10/MWh for later projects with capacities between 5-10 Mt CO_2 per year.

A coal-fired power plant enabled with CCUS presents an ideal opportunity to anchor a CCUS industrial hub since, if suitably sized, it could capture millions of tonnes of CO_2 each year. Typically, other industrial operations are only able to supply up to hundreds of thousands of tonnes of CO_2 annually, making them ideal complementary partners on a growing CCUS industrial hub. Establishment of an interconnected, appropriately-sized network hub that combines higher volumes of CO_2 from several large capture plants could result in even lower per MWh transport costs over the long term than the Task Force has estimated. At increased transport volumes, increasing costs would be associated with larger diameter pipelines and longer pipeline lengths that would facilitate the development of the storage hubs or clusters. However, these increased costs would be outweighed by the significant advantages afforded by the increased availability of CO_2 for EOR and value-added chemicals or for storage at dedicated facilities with associated carbon offsets.

The Aquistore injection well during its installation *(Courtesy: Petroleum Technology Research Centre)*

Advancing the Business Case

The CCUS industry is in its infancy. Significant potential exists to establish key business drivers for implementing a CCUS project. Presently, CCUS deployment efforts have yielded two industrial-scale facilities at coal-fired thermal power stations, along with 17 other facilities that have applied CCUS to a range of industrial processes. The limited number of installations points to the challenging nature of developing a good business case for CCUS in conjunction with coal power. BD3 and Petra Nova each rely on a significant revenue stream from CO_2 EOR. To enable the widespread acceptance of CCUS, all challenging aspects of the value stream must be addressed and improved.

Grid Support and Ancillary Services

Large thermal power stations play an important role in overall power grid response, including frequency disruptions, power factor correction, diversity of fuel source, and dispatchability. Renewable generation sources are growing in number and will continue to climb over the next decades. Ancillary services, in the form of quickly dispatchable backup power, are critical to managing the inherent intermittency of renewable energy. Deregulated markets with low amounts of reserve power generation capacity may experience price spikes during periods of instability that may be many times above the normal market level[31,32]. Consequently, open-market utilities may receive additional compensation for providing backup power from sources such as CCUS-equipped, coal-fired power plants.

It is therefore important that integration of a capture facility with its host power unit(s) does not adversely affect the provision of reliable, stable power. Interestingly, the magnitude of the parasitic load associated with CCUS deployed at a power facility is an opportunity to enhance its business case in the situation where it is possible to shut down capture operations over a short period in order to accommodate peaks in power demand, thereby enabling the power plant to maximize output to the grid. The first generation of facilities have limited capabilities in this regard. Consequently, considerations for flexible curtailment of CCUS operations must be made in future facility designs.

Renewable Energy Integration

Maximizing low emissions electricity is essential to driving down global emissions; renewable energy sources are critical to this strategy. Reliable backup power supply is essential to managing power supply interruptions that are characteristic of renewable energy sources.

The Shand Feasibility Study identified an unexpected potential environmental benefit from utilizing a CCUS-retrofitted, coal-fired power plant, rather than a natural gas power plant, as the source of backup energy for variable renewable generation sources. If backup energy is sourced from a natural

31 Siddiqui, A.S. Price-Elastic Demand in Deregulated Electricity Markets. Lawrence Berkeley National Laboratory, LBNL-51533. 2003. https://eta.lbl.gov/publications/price-elastic-demand-deregulated.

32 Trebing, H.M. A Critical Assessment of Electricity and Natural Gas Deregulation. Journal of Economic Issues. 2008. 42, 469-477.

gas plant, that power plant would be required to run at reduced loads to enable the integration of the maximum available power from renewable sources into the grid. However, a natural gas plant's efficiency decreases at reduced power output and its emission intensity profile increases accordingly if CCUS has not been deployed. Consequently, reducing the load of a natural gas plant to enable variable renewable generation effectively works against the non-emitting impact of variable renewable sources by increasing the emission intensity of the backup power supply.

In contrast, a CCUS-equipped, coal-fired power plant can increase its CO_2 capture rate when running at reduced load, thereby enhancing the environmental benefit of the renewable energy source by further reducing overall system emissions. This improvement may be achieved without any appreciable capital cost increases for the CCUS facility.

The Shand Feasibility Study estimated that the capture rate could increase from 90% at full load to 97% at the minimum power plant output level to support variable renewable energy sources which was determined to be 62% net output to the grid, at almost no additional capital cost. The integration of CCUS-equipped, coal-fired power generation with renewable energy is therefore an improved business case for CCUS retrofitting.

CO_2 Utilization Revenue & Storage Hubs

Key to the approval of the BD3 and Petra Nova projects was realizing value from the captured CO_2 that was utilized for EOR. However, sourcing CO_2 to meet the demand of an oil field from a single carbon capture plant is not without risk. An EOR operation requires a reliable supply of CO_2 to avoid interruptions in production. A single capture facility is prone to interruptions and trips from either the capture process or the associated power facility which prevents reliable supply of steady CO_2 volumes. Connecting two or more CO_2 sources to an EOR operation improves stability in CO_2 supply and reduces potential operating costs associated with CO_2 delivery challenges. As outlined above, when establishing a CO_2 hub under an appropriate CO_2-value regime, the business case for CCUS is improved, while its capital and operating costs are likely reduced, along with a reduction in the incremental cost of future transport and storage projects.

Surface monitoring equipment at the Aquistore CO_2 storage site. The BD3 Carbon Capture Facility (in background) sends CO_2 by pipeline for injection deep underground (3.4 km) and permanent storage *(Courtesy: Petroleum Technology Research Centre).*

An example of this CO_2 hub concept, the Alberta Carbon Trunk Line (ACTL), will be operational in Canada in late 2019[33]. The ACTL has been sized to transport 14.6 Mt of CO_2 per year in its 240 km pipeline that is expected to branch from a number of capture plants at different industrial facilities in a growing CO_2 hub. The transported CO_2 would be utilized for EOR and deep saline aquifer geological storage. At the present time, Wolf Energy has contracts in place to transport 4,400 tonnes per day of CO_2 captured at the North West Redwater Partnership's Sturgeon Refinery (1.2 $MtCO_2$/yr) and the Nutrien's Redwater Fertilizer production facility (0.3 $MtCO_2$/yr), both located northeast of Edmonton. The CO_2 will be utilized by Enhance Energy for EOR at its Clive oil field.

Similar CO_2 hub projects are emerging in the North Sea involving the UK, Norway and the Port of Rotterdam for the development of dedicated geological storage sites. The Port of Rotterdam may establish a CO_2 transport hub to serve The Netherlands' industrial facilities. It could expand to serve Belgium, Germany and/or the UK[34]. The proposed hub would, however, require an adequate carbon price or a significant subsidy for development to take place.

Impact of Technology Advancements on the Cost and Performance of CCUS

The economics of CCUS are steadily improving as a result of new technology development and associated innovations. Several decades of research, pilot, field, and commercial-scale projects have advanced various aspects of CCUS, leading to a dramatic reduction in costs. Currently, there are nearly 20 commercial CCUS installations operating in 9 nations, along with countless research and pilot projects on various aspects of CO_2 capture, utilization and storage ongoing around the world.

Capital and operating costs will continue to be whittled down through learning from commercial CCUS operations. However, technological progress has demonstrated that step changes in capital

33 Enhance Energy Inc. The ACTL Project. September 2019. https://actl.ca

34 Simon, F. Meet Europe's two 'most exciting' CO_2 capture and storage projects. Euractiv. April 3, 2018. https://www.euractiv.com/section/energy/news/meet-europes-two-most-exciting-CO2-storage-projects/

and operating costs are made through research and development aimed at reducing the costs of subsequent generations of advanced, first-generation technologies. The greatest gains can be made in reducing capture costs since they represent by far the largest proportion of capture and storage capital and operating expenses. Nonetheless, gains continue to be made in transport and storage cost reduction through deployment of technology innovations resulting from operational experience and research that is normally associated with large-scale testing and validation studies typically conducted in conjunction with the growing number of commercial CCUS operations. Suitable carbon utilization technology development is at a much earlier stage and represents an ongoing priority and opportunity for the growing CCUS industry.

Many capture technologies are at various stages of maturity. A select few are considered herein to demonstrate not only the breadth of current research ideas, but also to emphasize the need for continued investment in research and pilot-scale technology development, along with the next essential step of commercial deployment of the most promising technologies.

Post-Combustion Capture Technologies

Coal-fired power plants fueled by pulverized coal must deploy post-combustion processes, such as aqueous amine scrubbing systems that have been installed at BD3 and Petra Nova. There will continue to be improvements in driving down the costs of amine capture systems as additional installations are deployed. However, other types of technologies that show some promise for future commercial operation are at various stages of development. Among these is CO_2 capture using membranes. Suitable membranes have been tested that can capture CO_2 at rates of 30-90% with costs as low as US$30-40 per tonne, however, the cost of capture at the high end of this range is currently steep[35]. In February 2018, the United States Department of Energy announced funding for seven engineering-scale tests of various advanced carbon capture technologies[36]. Two of these projects will evaluate membrane capture systems, including a 1 MW_e-scale project at the Technology Centre Mongstad in Norway. Other capture technology studies at various engineering scales based on aqueous and non-aqueous solvents, mixed salts and membrane-sorbent hybrids were granted funding. A key objective of ongoing work is to optimize energy consumption and consumables to decrease the costs of capture, in addition to reducing capital costs.

Negative Emissions: Biomass Co-firing with Coal-Fired Power Generation

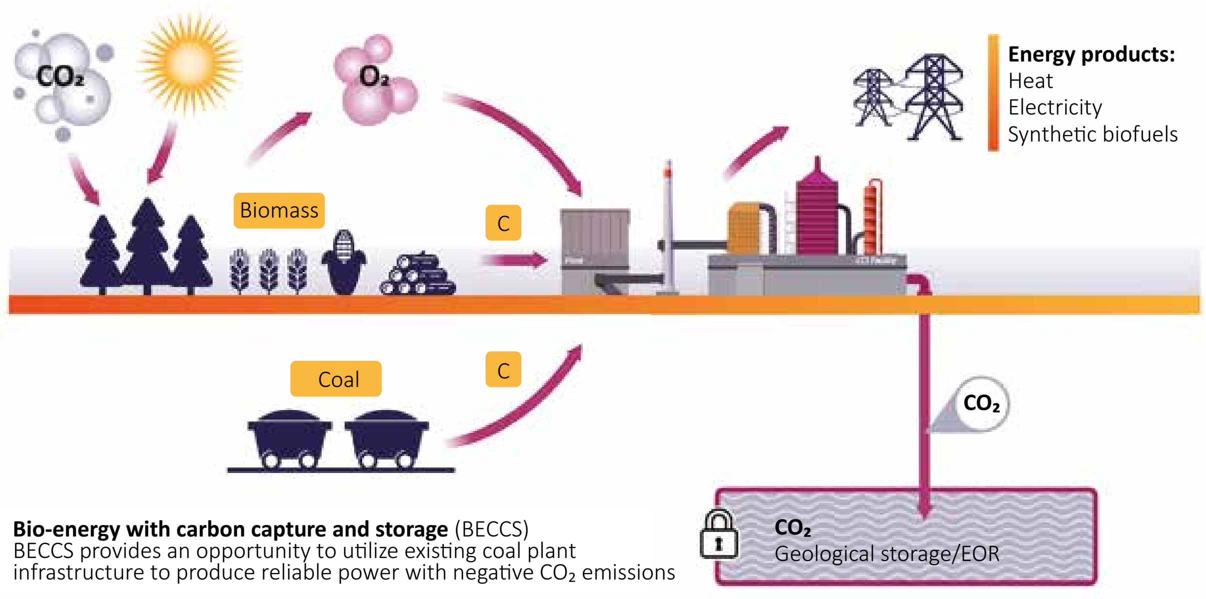
The 5th IPCC report indicated that three of the four pathways that would enable achieving a global temperature increase significantly below 2°C require removal of CO_2 from the atmosphere. This may be accomplished by Bio-Energy with CCUS (BECCS) that entails combustion of a sustainably-produced bio-fuel for energy generation, followed by CO_2 capture and permanent geological storage. A BECCS retrofit of an existing coal-fired power plant could result in the ability to operate with negative emissions intensity equivalent to the power plant's emission intensity when operated utilizing coal since the CO_2 removed during biomass growth is not re-emitted to the atmosphere. The potential emission intensity of a lignite power plant converted to BECCS could be as low as -1,100 t/GWh. The most significant constraint on BECCS deployment is the availability of sustainable biomass. Co-firing of coal with biomass[37] (*see Figure 8*) in existing coal power plants that have been equipped with CCUS can have a positive impact on the development of biomass as a fuel source.

35 Kniep, J. et al., Integrated Testing of a Membrane CO_2 Capture Process with a Coal-Fired Boiler. Presentation at the NETL CO_2 Capture Technology Review Meeting. August 8, 2016. www.netl.doe.gov/File%20Library/Events/2016/c02%20cap%20review/1-Monday/T-Merkel-MTR-Integrated-Membrane-Testing.pdf

36 United States Department of Energy. News Release. February 2018. https://www.energy.gov/articles/energy-department-invests-44m-advanced-carbon-capture-technologies-projects

37 CSIRO, Australia. Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass. IEA Greenhouse Gas R&D Programme (IEAGHG) Technical Report 2019-02. UK: IEAGHG, 2019. https://ieaghg.org/publications/technical-reports

Figure 8: *Bio-Energy Integration with Coal-Fired Power.*



Source: International CCS Knowledge Centre

Bio-energy typically comprises wood, woody waste and residue, crop waste, and purpose-grown biomass, including the growth of high-yield CO_2 crops that are suitable for marginal land and wastewater treatment. These fuel sources are often compressed into pellets that may be burned in a boiler, including a coal-fired boiler. Co-firing allows biomass to be blended with coal in varying amounts, depending on costs and biomass availability. For certain biomass types, blending with coal absorbs chlorine and other compounds from the biomass that would otherwise have a negative impact on emissions and air quality, as well as reliability of the boiler components and the carbon capture equipment. Some biomass sources can be effectively used without coal in existing facilities, supporting 100% biomass fuel, as has been successfully deployed at Drax power station in the UK.

BECCS experience is limited to date, with one commercial-scale installation capturing and geologically storing 1 Mt/y of CO_2 at a corn-to-ethanol plant in Illinois, United States[38,39]. Depending upon the sector, and whether or not a retrofit is possible versus new construction, it has been estimated that the cost of BECCS ranges from $15-400 per tonne of avoided CO_2, with bioethanol being the least expensive deployment option[40]. However, there are several factors that may encourage its development for power generation applications:

- A large number of coal-fired thermal power plants currently in existence could potentially be converted to fire biomass at reduced cost compared with constructing a new purpose built bio-energy facility. Appropriate timing is critical to assure conversion prior to anticipated power plant retirements and subsequent demolition by reusing exiting infrastructure and avoiding the significant capital cost associated with construction a new BECCS or biomass powered facility. For example, the newest coal-fired power plant in Canada is Keephills 3, a 450MW plant, that was commissioned in 2011, with an initial capital budget of $2B CAD. The cost to build a new, similar bioenergy thermal power facility, with or without CCUS, rather than retrofitting the existing facility, would delay development.

38 Archer Daniels Midland. ADM Begins Operations for Second Carbon Capture and Storage Project. 2017. https://www.adm.com/news/news-releases/adm-begins-operations-for-second-carbon-capture-and-storage-project-1.

39 McDonald, S. Illinois. Industrial Carbon Capture & Storage Project. Presentation. Bioeconomy 2017. July 11, 2017. https://www.energy.gov/sites/prod/files/2017/10/f38/mcdonald_bioeconomy_2017.pdf

40 Consoli, C. Bioenergy and Carbon Capture and Storage. Global CCS Institute. 2019. https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf.

- Existing coal fired power plants can be life extended almost indefinitely with a capital investment that is in the range of 10-15% of their replacement cost every 25-30 years.
- Experience with bio-energy at power stations would provide a suitable foundation upon which to build. Partial conversion of coal-fired power plants has taken place at several locations. The Drax power plant has achieved 100% biomass firing. This experience can be applied to subsequent biomass conversion of coal plants.
- The improvements in second-generation CCUS installations are key to making BECCS viable. The reduced capital and operating costs highlighted in the Shand CCS Feasibility Study are directly applicable to BECCS facilities.
- Biomass is generally sulfur-free thereby reducing the limestone consumption costs for SO_2 abatement and mitigating the impact of SO_2 slip into the CO_2 absorber with its negative impact on amine quality.
- BECCS conversions enable flexibility of energy supply. Conversion of power plants could maintain their ability to co-fire varying amounts of coal and biomass, matching seasonal and annual availability of biomass, including any supply disruptions.
- A staged launch of bio-energy power generation would support growth of feedstock supply. Biomass co-firing with coal would enable a gradual transition to increased biomass combustion, while the supply of biomass is established in regions with suitable growing conditions and in close proximity to coal-fired power station(s).
- An opportunity could emerge for agriculture and forestry operations located nearby a suitable coal-fired power plant by providing a new economic value stream from waste materials, such as straw and bark, in addition to new crops.
- Carbon offset credits from BECCS could have market value in certain regions. Negative emissions from BECCS could create a positive cash flow for the regions in which carbon credits are implemented to offset positive emissions elsewhere.

Oxy-Fuel Power Plant Technologies

In the future, capture at coal-fired power plants may be integrated into the power generation process either through pre-combustion or oxyfuel combustion[41]. Oxyfuel combustion is a coal-fired power technology that is promising and has been extensively explored at research and pilot scales over the past two decades. During oxyfuel combustion, coal is combusted in a process that uses pure oxygen instead of air. Fuel consumption is reduced due to the elimination of the other gaseous constituents in air, which comprises approximately 78% nitrogen. Pure oxygen is diluted with flue gas to avoid temperatures exceeding the specifications of commercial-scale boiler construction materials. The volume of flue gas produced during oxyfuel combustion is reduced approximately four-fold compared with thermal coal-fired power. Oxyfuel flue gas contains much higher concentrations of CO_2 due to the reduced volume of flue gas, along with a higher concentration of CO_2 compared with post-combustion flue gas (>60% vs 12-15%). Consequently, the capital and operating costs associated with purification and compression of the CO_2 can be significantly reduced. Oxyfuel combustion may also realize improved power plant efficiency due to increased coal utilization with an associated reduction in the parasitic power losses that are characteristic of post-combustion CO_2 capture power plant retrofits.

41 United States Department of Energy. Pre-Combustion Capture. 2019. https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd/pre-combustion-carbon

Callide Oxyfuel Project

A useful example to consider is the joint Australian-Japanese Callide Oxyfuel CCUS Project conducted during 2012-2015[42]. The follow key features of the project included[43,44]:

- The fuel used in the project comprised Callide coal, an Australian medium-ash, semi-bituminous coal, mixed with up to 25% of three other coals with low to medium ash content and bituminous and anthracite ranks.
- Coal was combusted at a rate of 20,000 kg/hr in a 30 MWe oxyfuel boiler.
- Boiler reliability of 90% was achieved within one month of operation.
- The flue gas, containing 68-70% CO_2, was filtered and scrubbed in a caustic process, followed by cryogenic separation of the CO_2 at a production rate of 75 t/day and a purity of 99.9%.
- Capture of more than 95% of SO_x, NO_x, particulates and trace metals was achieved.

The capital cost of a similarly-equipped oxyfuel retrofit of a full-scale, 420 MW_e supercritical boiler with 2.8 Mtpa CO_2 capture was estimated to be AU$2000-2300/kW[45], including transport and storage. This cost represents a decrease by approximately one third compared with the investment in the pilot plant. The overall operating and maintenance costs for the 420 MW_e oxyfuel capture facility were determined to be 1.5 to 2.0 times those for an ultra-supercritical coal-fired power plant; costs were evaluated without CCUS in both cases. These observations clearly demonstrate the impact of scale on capital and operating costs and the additional costs incurred by deploying advanced, first-generation technologies.

Callide A Power Station in central Queensland, Australia which was the site of the Callide Oxyfuel Project *(Courtesy: CS Energy Ltd)*

42 Spero, C. and Yamada, T. Callide Oxyfuel Project – Final Results. Oxyfuel Technologies Pty Ltd. March 2018. https://www.globalccsinstitute.com/resources/publications-reports-research/callide-oxyfuel-project-final-results/

43 Spero, C. Callide Oxyfuel Project – Lessons Learned. Global CCS Institute. May 2014.

44 Spero, C. Callide Oxyfuel Project. Presentation to the IEAGHG Oxyfuel Combustion Network. October 27-30, 2015. https://ieaghg.org/docs/General_Docs/5oxy%20presentations/Keynote%20Address/K03%20-%20C.%20Spero%20(CS%20Energy).pdf

45 Costs quoted in 2017 Australian Dollars (AU$).

Allam Cycle Pilot Project

The Allam Cycle is a novel power plant design that is based on pressurized, oxyfuel combustion technology. The steam used by conventional thermal power plants to generate electricity in a turbine is replaced with supercritical CO_2. Fuel combustion and power generation are integrated in the Allam Cycle. Like all oxyfuel combustion processes, the Allam Cycle uses oxygen for combustion and therefore requires an upstream air separation unit. Flue gas is produced during the cycle that is much higher in CO_2 than the flue gas generated by conventional combustion[42].

The Allam cycle is particularly promising since it produces CO_2, while generating power at a high efficiency, thereby potentially enabling electricity generation at rates that are competitive with conventional power plants without CO_2 capture capability. If CO_2 could be sold and/or incentives such as the US corporate tax code's Section 45Q tax credit were available, Allam Cycle power plants could be able to provide power at a significantly lower cost than unabated conventional plants. In other words, this system could result in the development of a power plant with negligible costs for CO_2 capture. The Allam cycle may be operated using natural gas, gasified coal, or biomass as its fuel source. A 50 MW_{th} demonstration of the natural gas-based cycle is located in La Porte, Texas, US[46]. Pilot-scale research is also being conducted on a 5 MW_{th}, lignite coal-based Allam Cycle at the Energy and Environmental Research Center, University of North Dakota[47,48].

46 NETPower. 2019. https://www.netpower.com

47 North Dakota Senate. News release. February 2018. https://www.hoeven.senate.gov/news/news-releases/hoeven-announces-700000-in-doe-funding-for-energy-and-environmental-research-center-at-und-to-develop-allam-cycle

48 Laumb, J. Advanced Coal-Fired Power Cycles. Presentation. 54th Annual Minnesota Power Systems Conference. November 2018. https://www.ccaps.umn.edu/documents/CPE-Conferences/MIPSYCON-PowerPoints/2018/AdvancedCoalFiredPowerCycles.pdf

Enhancing Public Policy Support and Financing

Fulfilling the goals of the Paris Agreement requires an international commitment to the deployment of CCUS as a key climate change mitigation strategy. Governments and financing institutions view CCUS as costly and seek other, lower-cost, emission mitigation projects to incentivize or fund, thereby inhibiting the development of effective policies and financing in support of CCUS deployment.

A tour group at the BD3 Carbon Capture Facility *(Courtesy: International CCS Knowledge Centre).*

Paradoxically, these very mechanisms would drive down the costs of CCUS, thereby assuring the essential cost reductions to incentivize new projects.

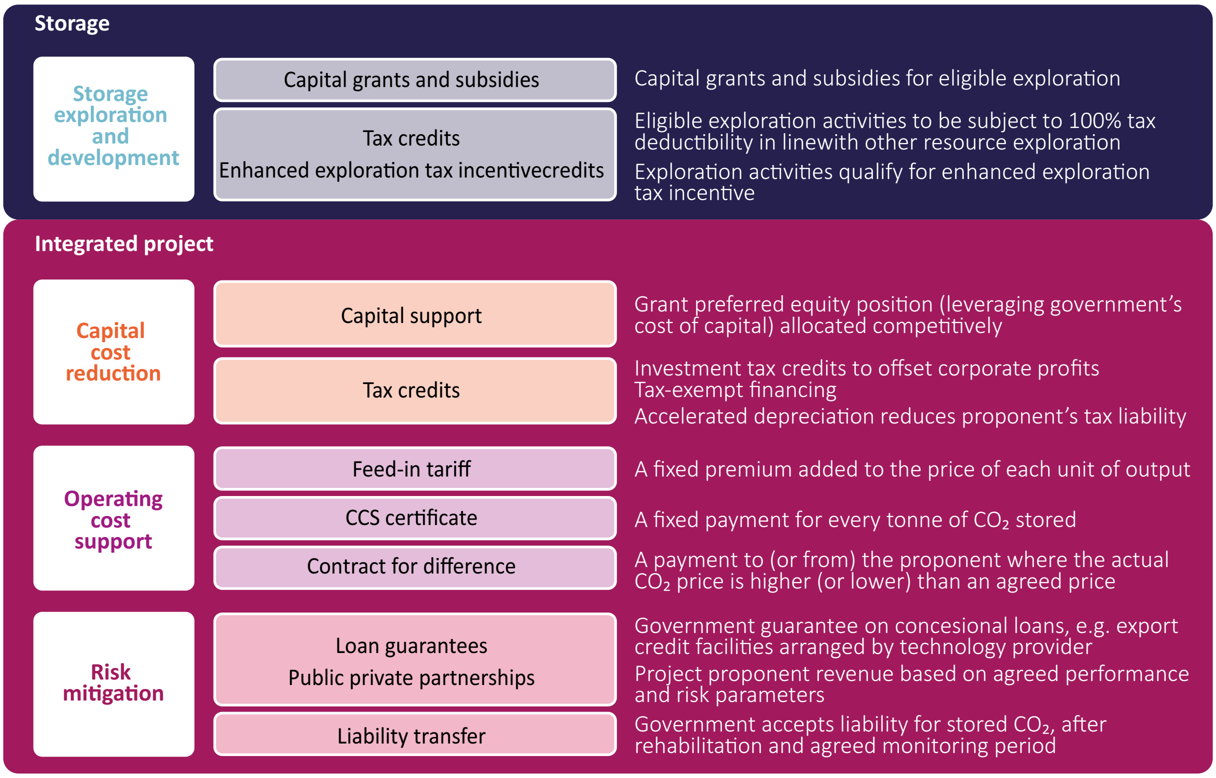
Although government policies must be tailored to a specific country, they may be grouped into the four broad categories as outlined in the 2016 CIAB report, namely:

- **STIMULATE CCUS MARKET UPTAKE** to substantially increase the level of CCUS deployment and investment capital. Policies must enable investment capital to earn a market-based rate of return and facilitate global CCUS deployment in energy and industrial markets while the technology matures.
- **SUPPORT PROJECT DEVELOPMENT.** The societal, emissions-reduction, and economic benefits of commercial-scale CCUS projects are immense. Applying lessons learned from existing projects and enacting policies to financially de-risk projects are both required to accelerate the CCUS project development process.
- **ENABLE PROJECT FUNDING.** Many countries have provided direct grant funding to CCUS projects. That approach continues to be important to improve project economics and strengthen access to investment capital that financially de-risks CCUS projects. Yet, that funding and investment are insufficient. Supportive public policy must be enacted. Low-carbon renewables have seen a global surge in market penetration due to similar policies. A parallel approach is essential for CCUS.

- **DEPLOY CCUS AND ADVANCE NEXT-GENERATION CCUS TECHNOLOGIES.** Traditional government focus on research and development is important. However, deployment of proven CCUS technology at large scale is critical to driving down costs and increasing deployment. Governments must continue to advance next-generation CCUS technologies and knowledge development that are pre-competitive or for which there are no identifiable market-based financial returns to assure future technology advancements.

Implementation of such policies would enable governments to achieve their commitments to the Paris Agreement at lower costs (*see Figure 9*).

Figure 9: *Policy Incentives to Improve the Economics of CCUS*



Source: Greig, C. et al. Energy Security and Prosperity in Australia – A Roadmap for CCS.[49]

A useful example to consider here are the recent improvements to the existing 45Q tax credit in the United States to incentivize CCUS deployment, particularly for the "low-hanging fruit" in the industrial sector, such as ethanol production, natural gas processing, and ammonia production. CCUS advocates have a renewed sense of momentum in the US due to the passage of The FUTURE Act, which reformed the existing 45Q tax credit with a purpose to spur CCUS deployment. The reformed 45Q tax credit provides:

- $35/tonne CO_2 for beneficial use, including EOR
- $50/tonne CO_2 for saline aquifer storage
- 12-year window for receiving tax credits
- Construction must begin by Jan 1, 2024
- Minimum capture rate: 500,000 tpy for power plants and 100,000 tpy for industry
- Transferrable, which means that non-profits such as cooperatives can use the tax credit.

49 Reprinted by the International Energy Agency. Five Keys to Unlock CCS Investment. Paris: IEA, 2017. https://webstore.iea.org/five-keys-to-unlock-ccs-investment.

However, 45Q may require additional policy enhancement to spur CCUS deployment in the power sector[50]. While tax credits are a viable approach to incentivizing energy technologies in the United States, they are not the same as cash, which may result in some significant challenges for some power companies attempting to capitalize on the tax credit, including:

- An insufficient corporate tax base to utilize 45Q credits.
- United States tax rates have been reduced, so CCUS credits have also decreased.
- Monetization of tax credits may be lower than anticipated due to the decrease in tax credit value by at least 20% on transfer to a project partner or through monetization.
- Tax credits cannot fund project capital costs since they are only available annually as the project stores CO_2 over time rather that at project outset. Financing will likely be required for project capital costs.

To understand the remaining challenges for the United States' coal sector, the lessons learned from the NRG Petra Nova project may be considered. NRG managed to avoid the challenges of the United States' New Source Review (NSR) environmental regulation by adding cost and complexity to the project through construction of a natural gas turbine to provide the capture facility's steam and energy needs. The NSR regulation is not without risk for CCUS projects since it requires industrial emissions to be reduced using "best available technology". Consequently, an NSR for the most efficient CCUS integration of an existing facility may trigger plant modifications that are uneconomic and/or reduce the intended emissions reduction target.

According to NRG, incorporating the lessons learned from the project would reduce the cost of a similar project today by 10-20%[51]. Although the Petra Nova Project, by comparison, is often cited to have cost about $1 billion, this includes the pipeline and a capital project to prepare the oil field to receive CO_2, costs that would not necessarily be incurred by all projects. The capital for the carbon capture facility, by comparison, were approximately $635 million for Petra Nova.[52] A new 240MW project, similar to Petra Nova, capturing about 1.4Mt per year for CO_2-EOR could be eligible for 12-years of 45Q tax credits that would be worth approximately $588 million, thus improving the rate of return on investment and reducing financing risk.

In addition to the positive nature of the reformed 45Q tax credit, many other public policy proposals are currently in development or under consideration that will facilitate new CCUS projects in the power sector, especially for coal. Regardless of the challenges the coal-fired power sector faces for CCUS deployment, new projects are being considered in the United States today. It is certainly possible that the very real reductions discussed throughout this document could become reality in the United States in the near term, and lessons learned at each successive project will continue to reduce future deployment costs.

50 Energy Futures Initiative. Advancing Large Scale Carbon Management: Expansion of the 45Q Tax Credit. May 2018. www.energyfuturesinitiative.org/news/2018/5/22/efi-policy-paper-how-the-45q-credit-may-spur-carbon-capture-innovation.

51 Richards, H. Carbon Dioxide from Coal Plants Has an Interested Buyer from Oil and Gas. If the Costs Come Down. Casper Star Tribune: October 2017. www.trib.com/business/energy/carbon-dioxide-from-coal-plants-has-an-interested-buyer-from/article_db13a06a-af61-52b5-858d-ff0330dc1e54.html.

52 Petra Nova Parish Holdings, LLC, W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project, www.osti.gov/servlets/purl/1344080

Conclusions

The objective of this report was to outline the long-term outlook for cost reductions from coal-fired power stations that capture and store CO_2 emissions using CCUS. *Figure 10* summarizes the key points outlined in this report. Existing projects provide significant lessons for future CCUS design and development; many will lead to dramatic capital and operating cost reductions. Work to date has successfully demonstrated the favorable economics of size and other factors to reduce the cost of CO_2 capture. Technological advancements will lead to further cost improvements. Promising new technological approaches, including membrane capture, oxyfuel combustion and BECCS have been highlighted accordingly.

Globally, there will be over 20 commercial-scale CCUS projects in operation by 2020, with more than 37 Mt of anthropogenic CO_2 being captured and geologically stored annually[53,54]. These projects serve to meet the 2010 G8 target set in Hokkaido in 2008[55], albeit a decade late. Only two of these projects involve CCUS-enabled, coal-fired power plants. A positive move forward in the deployment of industrial-scale, CO_2-utilization projects has taken place in the last few years that has significantly increased the number of commercially-viable technologies and the number of technology vendors that may be considered for upcoming projects. Furthermore, beyond the handful of nations that have undertaken large-scale CCUS, new pilot-scale CCUS projects and initiatives have been launched or are under development elsewhere.

In order to increase, or even maintain, the rate of CCUS deployment, a new commitment by G20 nations must be made to significantly increase CCUS installations. This is an essential next step in order to meet existing commitments under the Paris Agreement to increase CCUS deployment by 2030 and beyond. Continued progress will rely on the following:

- **IMPROVED UNDERSTANDING AND KNOWLEDGE.** Combining technical expertise to better understand the cost savings and design improvements for CO_2 capture must continue to facilitate progress.
- **REDUCED UNCERTAINTY ABOUT SHARED TRANSPORT AND STORAGE.** Facilitate necessary investment in the development of major infrastructure on transport and storage components, including better logistics planning.
- **STRENGTHENED POLICY AND FINANCIAL SUPPORT.** An international commitment must be made to establish supportive policy and innovative financing mechanisms to grow CCUS into a well-established industry.
- **CONTINUED INVESTMENT IN RESEARCH AND PILOT PROJECTS OF NEW TECHNOLOGIES, ALONG WITH COMMERCIAL CCUS DEPLOYMENTS.** The significant level of investment in research, piloting and demonstration over the past few decades must continue and, indeed, increase to help reduce investment risk associated with low emissions coal-fired power technologies. This will accelerate the technology development cycle. Research is also essential for independent and objective analysis, and generating data and developing expertise to accelerate design, permitting and operation of new coal power plants using specific black and brown coals in local conditions.

53 Zakkour, P. and Heidug, W. A Mechanism for CCS in the Post-Paris Era: Piloting Results-Based Finance and Supply Side Policy Under Article 6. Saudi Arabia: KAPSARC, 2019. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=24&ved=2ahUKEwjN84_9vPTkAhUTNn0KHefvBtA4FBAWMAN6BAgBEAI&url=https%3A%2F%2Fwww.kapsarc.org%2Ffile-download.php%3Fi%3D28368&usg=AOvVaw0QLVGqasyzuYweROMf3Dxp

54 IEAGHG. Paris Climate Change Targets Cannot be Met Without CCS. Greenhouse News. Issue 128. December 2017. https://ieaghg.org/docs/General_Docs/Publications/December_2017_LR.pdf.

55 Munk School of Global Affairs & Public Policy, University of Toronto. G8 Summits. Hokkaido Official Documents: Environment and Climate Change. Article 31. July 8, 2008. http://www.g8.utoronto.ca/summit/2008hokkaido/2008-climate.html.

Figure 10: *Summary of Cost Reduction Potential for CCUS at Coal-Fired Power Stations*

Storage

CO_2 Transport & Storage Cost Reduction

- Invest in CO_2 hubs and common user storage sites, ideally anchored by a large capture unit
- Plan for early phase surplus capacity in pipeline construction and installation to take advantage of the size-independent pipeline construction costs including trenching and securing of right of ways
- Plan trunk-line sections and feeder lines to maximize asset life
- Learn from others how to minimize infrastructure costs accounting for terrain, shoreline crossings & planning/environmental requirements

Integrated project

Capital & Commissioning Cost Reduction

- Build large facilities with higher capture rates to take advantage of economies of scale
- Choose site layouts to improve integration of the power and carbon capture plants and reduce interconnection and operation costs
- Include modular facility design to reduce on site construction costs and associated risks
- Balance complexity and efficiency based on local conditions and economic factors
- Choose high efficiency power plant hosts to reduce the relative impact of CCUS related parasitic load
- Develop CCUS supply chain for equipment to increase competition and spur innovation
- Stage and pre-plan power plant integration to reduce unit outage time during construction and commissioning

Operating Cost Reduction

- Reduce amine degradation costs by pre-validating the flue gas and amine compatibility
- Optimize maintenance tasks and scheduling to avoid unplanned work in order to reduce costs and production disruptions
- Re-use flue-gas produced water and waste water streams to reduce new water draws as well as disposal costs
- Improve digitalization and automation to maximize performance of the integrated operation
- Improve energy efficiency of capture (including compression), and source regeneration energy from lowest value heat source available
- Leverage operating knowledge of existing large-scale projects: e.g. health, safety, environment management, operating manuals and protocols

Advance the Business Case

- Appropriately value large coal generation units which provide grid security and ancillary services
- Enhance flexibility of coal-fired plants with CCUS to integrate with variable renewable generation sources
- Improve EOR operability and security by sourcing of CO_2 from multiple sources using transport hubs
- Invest in advanced technology research and pilot projects, along with commercial deployments
- Realize the potential value of negative emissions from biomass co-firing with CCUS to improve future economics and to allow a flexible expansion of biomass fuel sources
- Enhance policies and financing to enable private investors to realize benefits from expanded CCUS deployment

CCUS paired with coal-fired power generation is a global reality. While the application of CCUS in the power generation sector has been the primary emphasis of this report, applying the lessons learned from CCUS deployment at coal-fired power plants, as described herein, may be extended to other energy-intensive sectors as a CO_2 emissions reduction strategy and vice versa. Given the lack of available technology alternatives, many types of fossil fuel-based, emission-intensive processes will require CCUS to achieve the 2°C goal. Continued learning and knowledge from commercial CCUS installations at power plants will be directly transferable to energy-intensive industries, as will any policies and financial vehicles established to support rapid uptake of CCUS technology by the coal-fired power sector.

At the scale of emissions that may be captured from a single, large coal-fired power plant, these facilities present the unique opportunity to anchor CCUS hubs with additional, smaller industrial CO_2 sources supplementing supply for utilization and storage. The development of CCUS transport and storage infrastructure will be essential to increasing deployment of CCUS by fossil-energy-based sectors and must proceed in concert with any new CO_2 capture project development. Naturally, with the ability to rapidly build supply of CO_2, the number of end users in utilization and storage must also grow which will require appropriate government and financing levers to incentivize. Full-chain CCUS is vital to reducing global emissions in a growing world.

Recently, welcome and encouraging improvement in the pace and progress of commercial CCUS projects, undertaken in conjunction with coal-fired power and related energy-based industries, has been realized, thereby demonstrating the clear and positive commitment by industrial sectors to enhance knowledge, understanding, and critical know-how, that will inevitably lead to sustained improvement in the environmental performance of the coal power industry. Maintaining, or ideally increasing, momentum in commercial CCUS applications will make a meaningful contribution toward achieving the Paris Agreement's 2-Degree goal.