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CARBON CAPTURE, STORAGE AND UTILIZATION TO THE RESCUE OF COAL?

Global Perspectives and Focus on China and the United States

Sylvie CORNOT-GANDOLPHE

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Center for Energy

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Executive Summary

In most of the pathways that limit global warming to 1.5°C, capture of CO_2 from fossil-fuel or biomass-based installations and its long-term geological storage (carbon capture and storage - CCS and bio-energy with carbon capture and storage - BECCS) plays a crucial role. Three of the four Intergovernmental Panel on Climate Change (IPPC) pathways that limit warming to 1.5°C foresee significant amounts of CCS, including large amounts of BECCS to create negative emissions. Only in one pathway, CCS is avoided altogether and essentially replaced by drastic and unprecedented reductions in energy demand.

There is increasing policy support for CCS projects around the world. This renewed interest comes with different focuses than policies at the beginning of the 2000s, which had coal power plants as a focal point. Today, there is a growing focus on CCS in industrial and manufacturing applications. There is also a growing interest in hydrogen production combined with CCS in several countries.

The focus is not only on capture and storage but also on utilization of the carbon (CCUS) for applications like increasing output from oil wells (enhanced oil recovery or EOR) or as an input for creating useful products. However, outside EOR, the uses of CO_2 are limited. And if EOR can constitute an outlet for early CCUS projects to facilitate the deployment of the technology, it cannot respond to climate change challenges. CCUS is also changing its image. It is becoming part of a new carbon economy providing job and value creation.

Currently, there are 23 large-scale CCS/CCUS project in operation and construction in the world, with a capture capacity of 40 million tons per annum (Mtpa) of CO_2. Most of these projects come from processes with highly concentrated CO_2 streams, such as natural gas processing and chemical production facilities, and 70% of the capture capacity is in North America. Only two coal power units in the world have been retrofitted with carbon capture, one in Canada and one in the United States (US). In addition, among the 20 projects under development in the world, six projects (4 in China and 2 in South Korea) involve coal power plants. There is also one project under feasibility study in Canada. Altogether, CCS/CCUS projects based on coal power plants have a CO_2 capture capacity of 12.4 Mtpa and involve some 4 GW of coal capacity. The challenge to scale up the technology is enormous. The International Energy Agency (IEA) projects 210 GW of coal capacity fitted with CSS in 2040 in its Sustainable Development Scenario, which can be considered as optimistic though.

Carbon capture deployment in the power sector is particularly challenging, as the technology incurs a significant capital cost and energy penalty, while energy revenues are increasingly limited by non-baseload operation. Learnings from the two retrofit plants in operation indicate that substantive cost reductions (up to 67%) are possible, suggesting that CCS/CCUS could provide an important mitigation solution to CO2 emissions of some of the existing coal fleet. The role of governments will be essential to make CCS/CCUS a viable option in the coal power sector.

The US, which has a proven record and leadership in CCUS, recently adopted new fiscal incentives (45Q credit tax) to encourage private investment in the deployment of CCS/CCUS. The new incentive is expected to spur a new wave of investment in CCUS projects and help advancing CCS in the US. However, it is unlikely that the coal industry will benefit: changes in gas prices, decreasing costs of renewable energy sources (RES), and the ageing coal fleet don't favour investment in retrofit of coal power plants. Power utilities don't seem ready to embrace the technology due to the high cost and investment in the capture technology and the very uncertain future of coal in the US power sector. The hesitancy of utilities to retrofit coal power plants with carbon capture facilities represents a setback for the coal industry which had hoped carbon capture would help extend the lives of coal-fired power plants and thus coal mining.

China offers a different picture. The coal fleet is young and still generates the bulk of the country's electricity generation. With its high proportion of large, efficient and young coal power units, China offers an ideal case for minimizing carbon capture retrofit costs. However, despite an acceleration in research and development (R&D) efforts in recent years, CCUS is still in its infancy in China. The first large-scale CCUS project was commissioned in 2018. CCUS still faces many challenges: a lack of policy operability; not enough commercial investment; and underdeveloped public participation. Crucially, China still lacks a regulatory framework for CCS/CCUS and storage of CO2 (beyond EOR-based storage) and financial incentives for projects. The attitude of coal power utilities towards future CCS/CCUS development pace is cautious. Concerns stem from the technology's maturity and cost, as well as the worrying prospect of coal power. Since RES have been rapidly deployed and their cost reduced, the coal power sector is facing increasing competition. In recent years, the annual operating hours of coal power plants have significantly declined. In addition, power utilities are having financial difficulties due to higher coal prices. Under these conditions, and without policy incentives, there is no economic business case to retrofit coal power plants with carbon capture equipment. If CO_2 prices rise in the future, driven by the new national carbon market, economic incentives to retrofit coal power plants could be provided. But CCS/CCUS in China entails logistic challenges as the transport and storage infrastructure has to be created. Currently, a large-scale deployment of CCS/CCUS in China remains uncertain. China is formulating a longer-term plan for greenhouse gas (GHG) emissions reductions until 2050, which is expected to inform future international commitments and provide clarifications on the role of CCS/CCUS.

From a global perspective, while CCS/CCUS could provide a solution for the decarbonisation of the coal power sector, mainly in emerging Asia, market and policy design as well as technological progress will ultimately determine the viability of CCS/CCUS in coal power generation. The current lack of progress implies that, if it is to be part of the mitigation options, efforts to help CCS/CCUS become commercially viable need to be stepped up.

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Introduction

With the Paris Agreement, most countries in the world have agreed to hold global warming well below 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C. The IPCC 2018 Special Report (SR1.5) shows that it is necessary to control global warming at the level of 1.5°C above pre-industrial levels to limit major climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth.[1] The impacts of a 2°C temperature rise are significantly more severe and costly than for 1.5°C, and several are practically irreversible. Pathways consistent with a 1.5°C global warming involve urgent and rapid global responses to reach net zero emissions by mid-century.

Meeting the world's growing demand for energy while also reducing carbon emissions is an enormous challenge for the 21st century. Modelled global energy pathways limiting global warming to 1.5°C generally meet energy demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C. But shifting the balance in the world's energy mix from a reliance on fossil fuels to renewable energy sources (RES) and nuclear energy will require considerable time. In the IEA Sustainable Development Scenario, by 2040, despite efficiency efforts and rapid development of RES, still 60% of primary energy supply come from fossil fuels. Carbon sinks are necessary to permanently store CO2 emissions from the combustion of fossil fuels.

In most of the pathways that limit warming to 1.5°C, capture of CO2 from fossil-fuel or biomass-based installations and its long-term geological storage plays a crucial role. Further, as was seen in IPCC's AR5 Report, removing carbon capture and storage (CCS)[2] from the portfolio of available options significantly raises mitigation costs. The IPCC has developed four main pathways limiting warming to 1.5°C. They are characterized by energy demand reductions, decarbonization of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and CCS to neutralize emissions from sources for which no mitigation measures have been identified. Three of the four scenarios foresee

1. Intergovernmental Panel on Climate Change (IPCC), *Special Report Global Warming of 1.5 °C*, October 2018, available at: www.ipcc.ch.

2. Please note that the IPCC report refers to CCS only and does not differentiate CCS and CCUS. On the contrary, the IEA refers to CCUS for all projects.

significant amounts of CCS, including large amounts of BECCS to create negative emissions. Only in one pathway, CCS is avoided altogether and essentially replaced by unprecedented reductions in energy demand: for example, the average annual decline of oil demand from today till 2030 in this scenario would be twice as large as the decline triggered in 2008/2009 by a combination of $140 per barrel and the global financial crisis.

With the exception of this low demand pathway, other 1.5°C-consistent pathways indicate that hundreds of gigatons of CO2, possibly over a thousand, would be stored underground until 2100. Thus, a rapid scaleup of CCS is essential for meeting climate and emissions targets while not crippling economic growth.

The focus is not only on capture and storage but also on utilization of the carbon (CCUS) for applications like increasing output from oil wells (enhanced oil recovery or EOR) or as an input for creating useful products. However, outside EOR, the uses of CO2 are limited. And if EOR can constitute an outlet for early CCUS projects to facilitate the deployment of the technology, it cannot respond to climate change challenges. CCUS is also changing its image. It is becoming part of a new carbon economy providing job and value creation.

This note looks at the renewed interest for CCS and CCUS globally in all energy sectors. It then focuses on the coal power sector only. It assesses the role they could play to reduce CO2 emissions from coal generation, notably in the US - given the US proven record in CCS and newly-introduced tax incentives - and in China, given the importance of coal-fired electricity generation in the country.

Growing Policy Attention and Support for CCS

CCS/CCUS is one of the crucial solutions to 1.5°C-consistent pathways and has moved up in the energy and climate agenda. Concurrent with the IPCC message, **there is increasing policy support for CCS/CCUS projects around the world**. According to the Global CCS Institute, 2018 may well go down as the year when the stars started to again align for CCS.[3] Indeed, in 2018 and in the first months of 2019, and for the first time in quite a long time, decisive actions have been taken from a number of governments to include CCS/CCUS in their policy. Among them, the major ones are the following:

- The **US enactment of 45Q** (tax credit) legislation (see below).
- The creation of the **United Kingdom Carbon Capture Utilization and Storage (UK CCUS) Council**, and the **CCUS Cost Challenge Taskforce**. The UK's vision is to become a global leader in CCS/CCUS, unlocking the potential of the technology and securing the added value which it can bring to industrial centres and businesses all across the UK.[4] The government has developed an **Action Plan** designed to enable the development of the first CCS/CCUS facility in the UK, commissioning from the mid-2020s. This would help to meet the UK ambition of having the option to deploy CCS/CCUS at scale during the 2030s, subject to costs coming down sufficiently.
- The progression of **Norway's full-chain industrial project** with government funding of $33 million allocated to the CCS project.
- The provision by the European Union (EU) of **additional funding to CCS/CCUS** projects through the EU Emissions Trading System Innovation Fund and the Horizon Europe research and innovation fund. The Innovation Fund will mobilise **€10 billion** to support low-carbon demonstration projects in energy intensive industries, renewable energy, energy storage and CCS/CCUS sectors. The first call is expected to be launched in 2020.

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3. Global CCS Institute (2018), *The Global Status of CCS – 2018*, available at: www.globalccsinstitute.com and "CO2RE Database", available at: www.globalccsinstitute.com.
4. UK Government, "Clean Growth: The UK Carbon Capture Usage and Storage Deployment Pathway. An Action Plan", 2018, available at: https://assets.publishing.service.gov.uk.

- In the **Netherlands**, the launch of the Port of Rotterdam CCS Backbone Initiative **(Porthos)** for the large-scale decarbonisation of refining, power and petrochemical clusters. The ambition is to store 2 Mtpa of CO_2 from 2021 and up to 5 Mtpa by 2030. In **France**, Arcelor, Total, Axens and Ifpen launched an EU-funded project at Dunkirk to store CO_2 from an industrial site as from 2021, with an ultimate ambition to store 10 Mtpa by 2035. Its developers claim to have brought down sequestration costs to less EUR 30/tonne, twice less than the global average.[5] If confirmed, this could be a game changer.
- CCUS deployment in **China** with the first large-scale CCUS project commissioned in April 2018 (see below)
- **Japan**'s commitment to establish a hydrogen society by 2030, and to create a Hydrogen Energy Supply Chain (HESC) in Australia.
- Interest in CCUS in **India**, where state company Oil and Natural Gas Corporation (ONGC) and IL&FS Tamil Nadu Power Company Ltd (ITPCL) have signed a memorandum of understanding to develop CCUS by injecting CO_2 captured at ITPCL thermal plants into oil fields of ONGC Cauvery Asset for EOR.[6]
- The establishment of a **CCUS centre of excellence in Indonesia**, with funding from the Asian Development Bank.

New focuses

The focus of new CCS/CCUS projects is different from those envisaged at the beginning of the 2000s, when CCS/CCUS projects targeted coal-fired power plants mainly. But efforts to develop the technology faded due to low carbon prices, lack of a business case, funding and social resistance. As the Global CCS Institute writes: "CCS first started to gain recognition in the 2000s as a means of capturing emissions from the dirtiest source of energy: coal-fired generation. This perception, that CCS is about delivering 'clean coal', coupled with the fact that its deployment globally has been slower than predicted has hung an albatross around its neck."[7]

5. M. Delamarche, "ArcelorMittal, Axens et Total s'attaquent au CO2 industriel", *L'Usine Nouvelle*, 29 May 2019, available at : www.usinenouvelle.com.

6. "Carbon Capture Projects in Asia", *Carbon Capture Journal*, November-December 2018.

7. GCCS Institute, "Why Carbon Capture Could Be the Game-Changer the World Needs", *Insights*, 23 March 2019, available at: www.globalccsinstitute.com.

Now CCUS is back in a new form, with a focus not only on capture and storage but also on "**utilization**," or "use," of the carbon for applications like increasing output from oil wells (EOR) or as an input for creating useful products. It should be mentioned, however, that outside EOR, the uses of CO_2 are limited. The conversion of CO2 into products cannot mitigate GHG emissions at the large-scale required to reach international climate change targets; however, finding use for CO2 where EOR or storage is not available is an emerging option. Similarly, EOR can constitute an outlet for early CCUS projects to facilitate the deployment of the technology, but cannot either respond to the climate change challenge.

A second shift is the focus of new CCUS projects on **industrial and manufacturing applications** in several regions of the world. Industries like refining, petrochemicals, cement and steel production, together generate about 20% of global GHG emissions. Decarbonizing these sectors is even more challenging than decarbonizing the power sector as most of these industrial processes require either carbon in their chemistry or high heat input, neither of which electricity is able to provide. CCUS deployed at scale is thus the necessary bridge to a "**just transition**" in which the global energy system can run on cost-competitive renewables and storage technologies alone.

The growing interest in **hydrogen** in several countries is reshaping the prospects of CCS/CCUS. The production of hydrogen is strongly connected with carbon capture in multiple ways.[8] The most basic is the source of hydrogen: today it is fossil fuels with over 10 tons of CO2 emitted for a ton of H2. Capturing it is one of the possible pathways for clean H2. There are already operating projects in Canada, the US and the United Arab Emirates. Those use the hydrogen locally in an industrial process, but there are much ambitious initiatives, such as the Australian initiative to produce H2 from Australian coal with CCS/CCUS and export it to Japan. CCS/CCUS could play a pivotal role in the huge challenge of decarbonising heat, through the development of the hydrogen economy, especially in countries with advanced gas networks, such as the United Kingdom.

CCS/CCUS is also changing its image. It is becoming part of a **new carbon economy** providing job and value creation. As the Global CCS Institute states, policies and financial support from governments along with private investment to commercialise CCS/CCUS not only promote real solutions to climate change, they also drive job opportunities and economic development.

8. L. Varro, "Commentary: Carbon Capture, Utilization and Storage Finally Catches the Spotlight", IEA, 7 December 2018, available at: www.iea.org.

Diverging views on the role of CCS/CCUS in the coal power sector

Despite global renewed interest in CCS/CCUS and growing CO_2 emissions from coal generation, there is no consensus between key institutions on the role of CCS/CCUS in the coal power sector.[9]

According to the Global CCS Institute, CCS/CCUS can have a role to play in the power sector in some regions, as most emissions linked to energy infrastructure are already essentially locked-in. Coal-fired power plants, which account for one-third of energy-related CO_2 emissions today, represent more than a third of cumulative locked-in emissions to 2040. Most of these plants are in Asia, where average coal plants are just 11 years old with decades left to operate. Looking ahead, more than 200 GW of coal capacity is under construction globally with 300 new plants to come online in the next few years in India and China alone. Rapid closure of coal-fired power plants in these countries seems economically and politically infeasible. CCS/CCUS is the only technology that can truly decarbonise these facilities.

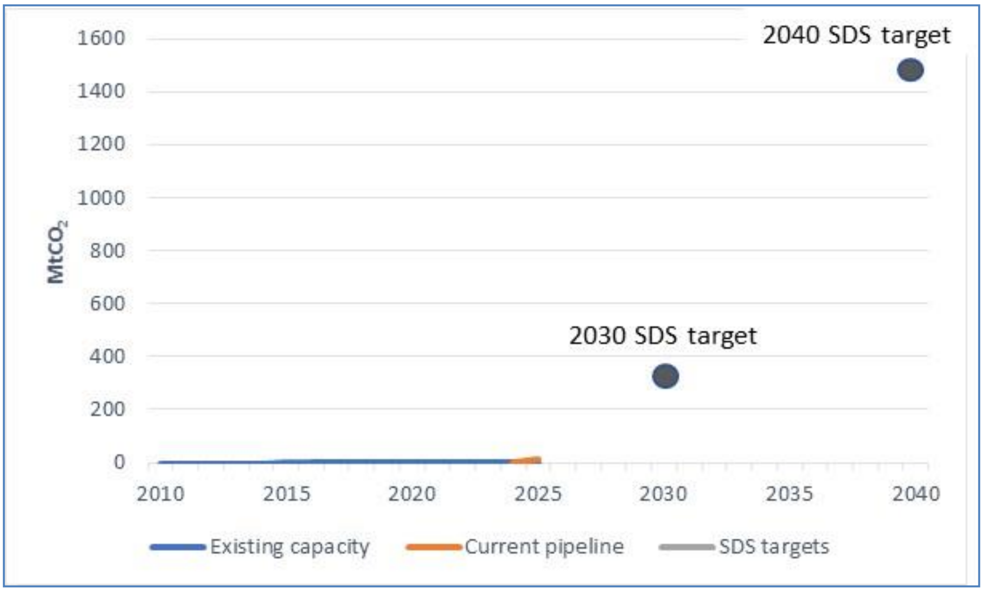
In the IEA Sustainable Development Scenario, CCS/CCUS in the power sector, and notably in the coal power sector, plays a crucial role in reducing emissions. CCS/CCUS from both power generation and industrial facilities grows over the course of the Sustainable Development Scenario: total CO_2 captured worldwide rises from 150 $MtCO_2$ in 2025 to 710 Mt in 2030 and nearly 2,400 Mt CO_2 in 2040. In the power sector, CCS/CCUS is deployed on coal and gas fired power plants. Around 350 Mt CO_2 are captured in the power sector by 2030, a figure that rises to almost 1500 Mt CO_2 by 2040.[10] As seen previously, some 210 GW of coal plants worldwide are fitted with CCS/CCUS by 2040 (20% of the coal fleet), of which 170 GW are retrofits to existing plants. CCS/CCUS in power generation only really makes significant inroads in China (150 GW in 2040) and the US. The IEA highlights that

9. At the opposite, there is consensus between different institutions on the role of CCS/CCUS for gas-fired power plants. According to the Global CCS Institute, in OECD countries, renewable intermittency poses a real challenge to grid operators. Zero-emission electricity is central to the future electricity mix but balancing services are likely to continue to be dominated by gas-fired plants for several decades yet. CCS/CCUS is necessary to reduce emissions from these gas-fired power plants. The IPPC models come to the same conclusion. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3-11% interquartile range) of global electricity in 2050. In the WEO 2018 Sustainable Development Scenario, natural gas replaces coal as a lower-carbon alternative for mid-load and baseload use in the next decade, serving as a flexible power source to support the integration of variable renewables. The overall level of gas use in the power sector peaks just before 2030 and then declines by more than 3.5% a year below current levels in 2040. Gas-fired power plants would be fitted with CCS/CCUS starting in 2025 and reach just over 1% of global gas-fired capacity by 2040. (www.iea.org)

10. IEA, "CCUS in Power, Tracking Clean Energy Progress", 25 January 2019, available at: www.iea.org.

progress in CCS/CCUS deployment and investment remains limited in practice and lags behind the pace that would be needed in this scenario.

Graph 1: Large-scale CO2 capture projects in power generation in the IEA Sustainable Development Scenario



Includes coal and gas power plants.

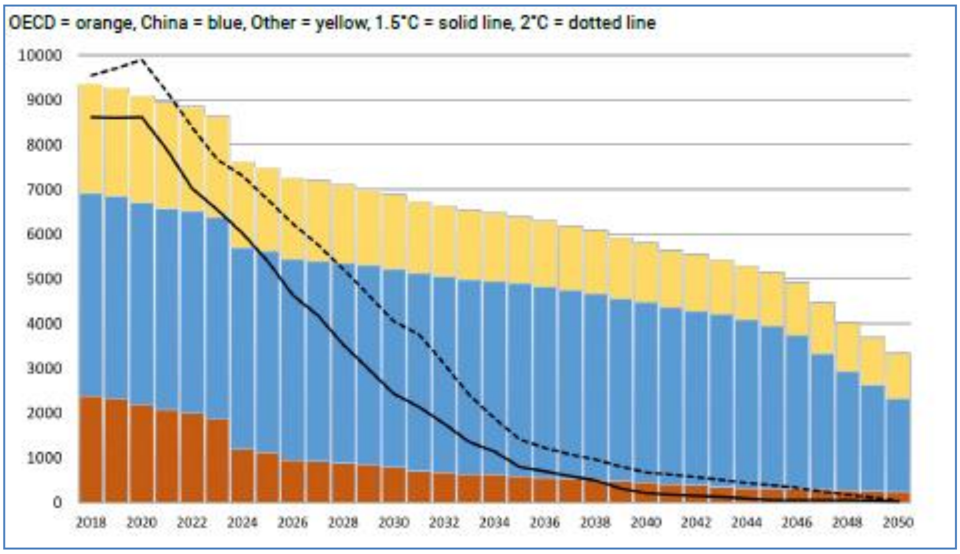
Source: IEA WEO 2018 Sustainable Development Scenario (SDS).

At the opposite, as coal is almost completely phased out in the electricity sector, there is not much **CCS on coal-fired power plants in the IPCC pathways**. CCS is done almost exclusively on gas (including on gas-fired power plants), on biomass and on industry, especially after 2050. The models opt for closing coal-fired power plants; even with CCS, coal-fired power plants are not attractive enough, based on the assumptions. In 1.5°C pathways, renewables are projected to supply 70–85% (interquartile range) of electricity generation in 2050. Shares of nuclear and natural gas with CCS are modelled to increase in most 1.5°C pathways with no or limited overshoot, while **the use of coal shows a steep reduction in all pathways and would be reduced to close to 0%** (0–2% interquartile range) of electricity generation by 2050.[11] While acknowledging the challenges and differences between the options and national circumstances, the IPCC states that political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years. These improvements signal a potential system transition in electricity generation.

11. IPCC, *op. cit.*

The graph below from Global Energy Monitor (formerly CoalSwarm), Sierra Club and Greenpeace shows IPCC estimates on coal power for the 1.5°C and 2°C targets[12] against the power produced from all currently operating plants utilized at the global average rate over an average lifetime (52.8% capacity factor and 40 years).[13] It clearly shows that electricity produced from currently operating coal power capacity in the world will largely exceed the median limits estimated by the IPCC to keep global warming at 1.5°C and 2°C. To hold temperatures at 1.5°C or 2°C above pre-industrial levels, either coal plant use will have to rapidly decline and retirements accelerate, or CCS/CCUS will have to be rapidly deployed on coal power plants.

Graph 2: Electricity produced from currently operating coal power capacity vs. IPCC median limits (TWh)



Source: Global Energy Monitor, Sierra Club, Greenpeace.

While the views diverge on the role of CCS/CCUS in the coal power sector, the message of the three key institutions is clear: **there is no future for unabated coal power in a 2°C scenario, and even more so in a 1.5°C.** Keeping coal in the electricity mix therefore depends on the deployment of CCS/CCUS in the sector. The next sections look at the development of global CCS/CCUS projects, notably those related to coal power plants and trends in the US and China.

12. Median of the 1.5°C scenarios with no to limited overshoot and 2°C scenarios with a 66% probability, without carbon capture and storage.

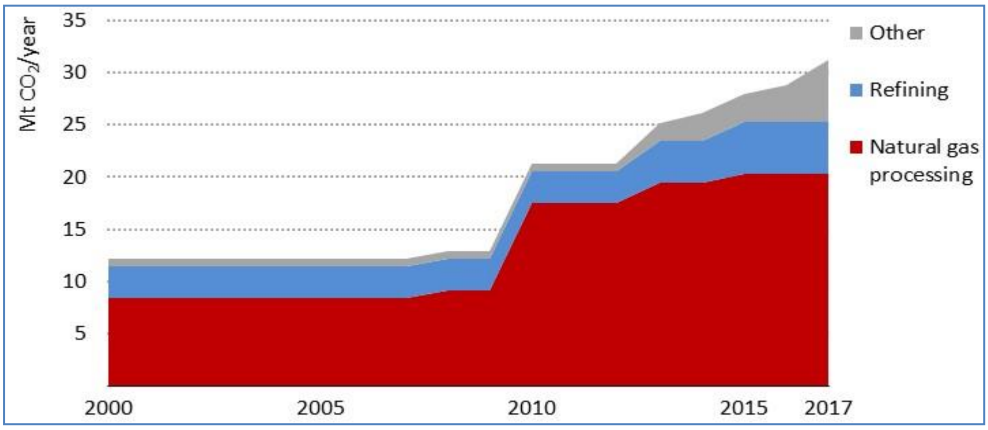
13. Global Energy Monitor, Sierra Club, Greenpeace, Boom and Bust 2019 – Tracking the Global Coal Plant Pipeline, March 2019, available at: https://endcoal.org.

Global status of CCUS

According to the Global CSS Institute's CO2RE database, there are **18 large-scale CCS/CCUS facilities**[14] **in operation, capturing 33 Mtpa of CO2** and 5 projects under construction, with a capacity to capture almost 7 Mtpa of CO2.[15] A further 20 large-scale projects are in various stages of development. In addition, several small-scale CCS/CCUS projects collectively capture some 3 Mtpa of CO2.

Of the 33 Mt of carbon capture capacity currently in operation around the world, around **90% comes from processes with highly concentrated CO2 streams** that are relatively easy and cost-efficient to capture, such as natural gas processing and chemical production facilities.[16] An estimated **80% are in the oil and gas sector** (two-thirds in natural gas processing, where separation of CO2 is a necessary step in the preparation of natural gas for injection into the pipeline network) and **70% are in North America**, largely due to its mature CO2-EOR industry.

Graph 3: Historical volumes of CO_2 captured globally



Source: IEA, World Energy Outlook 2018.

Revenues from the sale of captured CO2 for EOR have been the principal means to bring many large-scale CCUS facilities to market. Thus **18 CCUS facilities currently in operation or construction make use of EOR.** The IEA highlights the role CO2-EOR could play to provide a cost-effective way to deploy CCUS.[17] The oil revenues generated reduce project costs and

14. Large-scale CCS facilities are facilities with annual CO2 capture capacity of 400,000 tons or more.
15. Global CCS Institute, "CO2RE Database, Facilities Database", available at: https://co2re.co.
16. IEA (2018d), *World Energy Investment 2018* (WEI 2018), July 2018, available at: https://webstore.iea.org.
17. IEA (2018b), *World Energy Outlook 2018* (WEO 2018), November 2018, available at: www.iea.org/weo2018.

expand the amount of CO_2 stored per unit of investment. If a number of projects of this kind were developed, this would be likely to reduce the costs of CCUS more generally over time through learning by doing.

Only five CCS projects use dedicated geological storage and store around 4 Mtpa of CO_2. These projects were driven by regulation/policies that encourage CO_2 emission reductions. **Among these projects are the Sleipner CO_2 capture project in Norway, which has injected 1 Mtpa of CO_2 since 1996** and the Snovhit CO_2 capture project (0.7 Mtpa of injected CO_2). A significant tax on CO_2 emissions from the offshore oil and gas industry in Norway has enabled these two large-scale, gas-processing based projects, highlighting that industries with strong revenue and low capture costs are better able to absorb the added cost of CCS. Another project close to the Troll field is also expected to be developed soon. With the commissioning of the western Australian Gorgon CO_2 injection project at the end of 2019, the amount of CO_2 stored in dedicated gas storage will double. The western Australian Environmental Protection Act of 2009 requires that at least 80% of the CO_2 extracted from the gas reservoirs over any five-year period is injected underground.

Nine countries have developed or are constructing CCS/CCUS projects (see Table 2). These experiences clearly illustrate that **CCS/CCUS has been demonstrated in a large number of applications**. The major barrier to deployment is no longer technological, but political and commercial.

There is a **revival of CCS/CCUS projects in Europe**. In 2018, six new large-scale CCS/CCUS facilities have been added to the Global CCS Institute database. All are in Europe and mainly related to CCS/CCUS decarbonised hydrogen production. This revival is led by the United Kingdom, which has now five CCS/CCUS projects at an early stage of development, of which three for H_2 applications (H21 North of England, HyNet North West, Acorn Scalable CCS Development), the Netherlands (Port of Rotterdam CCUS Backbone Initiative (Porthos) and Hydrogen 2 Magnum) and Ireland (Ervia Cork CCS). In France, a first experiment by Air Liquide has been conducted at a hydrogen plant, where a 100 000 tonnes/year CO_2 capture and purification unit via a cryogenic process was commissioned end 2015.

The current resurgence in CCS/CCUS deployment will create **a new wave of CCS/CCUS facilities in the 2020s**. But CCS/CCUS has still to make progress in demonstrating its commercial viability. Moreover, the current pipeline of large-scale CCS/CCUS deployment does not come close to the CCS/CCUS component needed to meet Paris Agreement climate goals. According to the Global CCS Institute, **over 2,500 large-scale CCS/CCUS facilities will be needed by 2040 to reach the Paris 2°C targets.** This equates to more than 100 facilities entering operation each year between 2020 and 2040.

Table 1: Large-scale CCS/CCUS projects, in operation, under construction and completed

Project name	Country	State / district	Starting date	Source of CO_2	CO_2 capture capacity (Mtpa)	Primary storage type
OPERATING PROJECTS						
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	United States	Texas	1972	Natural gas processing	0.4-0.5	EOR
Enid Fertilizer CO_2-EOR Project	United States	Oklahoma	1982	Fertiliser production	0.7	EOR
Shute Creek Gas Processing Plant	United States	Wyoming	1986	Natural gas processing	7.0	EOR
Sleipner CO_2 Storage	Norway	North Sea	1996	Natural gas processing	1.0	Dedicated storage
Great Plains Synfuel Plant and Weyburn-Midale Project	Canada	Saskatchewan	2000	Synthetic natural gas	3.0	EOR
Snøhvit CO_2 Storage	Norway	Barents Sea	2008	Natural gas processing	0.7	Dedicated storage
Century Plant	United States	Texas	2010	Natural gas processing	8.4	EOR
Petrobras Santos Basin Pre-Salt Oil Field CCS	Brazil	Santos Basin	2013	Natural gas processing	1-2.5	EOR
Coffeyville Gasification Plant	United States	Kansas	2013	Fertiliser production	1.0	EOR
Air Products Steam Methane Reformer EOR Project	United States	Texas	2013	Hydrogen production	1.0	EOR
Lost Cabin Gas Plant	United States	Wyoming	2013	Natural gas processing	0.9	EOR
Boundary Dam Carbon Capture and Storage Project	Canada	Saskatchewan	2014	Power generation	1.0	EOR
Quest	Canada	Alberta	2015	Hydrogen production	1.0	Dedicated storage
Uthmaniyah CO_2-EOR Demonstration Project	Saudi Arabia	Eastern Province	2015	Natural gas processing	0.8	EOR
Abu Dhabi CCS Project (Phase 1)	United Arab Emirates	Abu Dhabi	2016	Iron and steel production	0.8	EOR
Illinois Industrial Carbon Capture and Storage Project	United States	Illinois	2017	Ethanol production	1.0	Dedicated storage
Petra Nova Carbon Capture Project	United States	Texas	2017	Power generation	1.4	EOR
CNPC Jilin Oil Field CO_2-EOR	China	Northeast China	2018	Natural gas processing	0.6	EOR
UNDER CONSTRUCTION						
Gorgon Carbon Dioxide Injection	Australia	Western Australia	2019	Natural gas processing	3.4-4.0	Dedicated storage
Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream	Canada	Alberta	2019	Fertiliser production	0.3-0.6	EOR
Alberta Carbon Trunk Line (ACTL) with North West Sturgeon Refinery CO_2 Stream	Canada	Alberta	2019	Oil refining	1.2-1.4	EOR
Sinopec Qilu Petrochemical CCS	China	Shandong Province	2019	Chemical Production	0.4	EOR
Yanchang Integrated Carbon Capture and Storage Demonstration	China	Shaanxi Province	2020-21	Chemical Production	0.41	EOR
COMPLETED PROJECTS						
In Salah CO2 Storage	Algeria		2004 (closed in 2011)	Natural gas processing	1.0	Dedicated storage

Source: Global CCS Institute.

CCS/CCUS in the Coal Power Sector

There is limited experience on carbon capture-fitted coal power plants. Today, only **two projects capture 2.4 Mt of CO2 annually.** They are operating as baseload capacity applying post-combustion capture technology:

- **Boundary Dam 3 Carbon Capture and Storage Facility (BD3)** (115 MW of capacity) at the Boundary Dam coal–fired power station in Saskatchewan, Canada, completed a refurbishment program in October 2014 that included retrofitting CO2 capture facilities with a capture capacity of approximately 1 Mtpa of CO2. The majority of the captured CO2 is transported via pipeline and used for EOR at the Weyburn Oil Unit, also in Saskatchewan. A portion of the captured CO2 is transported via pipeline to the nearby Aquistore Project for dedicated geological storage. SaskPower, the operator of the BD3 unit, had to invest more than $330 million to rebuild the power block at the plant to ensure its operational lifespan would match that of its carbon-capture retrofit. The total cost of the project was approximately $1.1 billion. The BD3 project was aided by a one-time CAD$240 million ($180 million) grant from the government of Canada. BD3 is capable of reducing the CO2 emissions from the coal process by up to 90%. Since operational start-up and up to March 2019, the facility has captured 2.6 Mt of CO2.[18] The facility had to address safety issues when it started up. Now, it has started to demonstrate a level of reliability that is consistent with a thermal-generating facility, although still at below design CO2 production levels.[19]
- The **Petra Nova Carbon Capture project** in Texas, US, commissioned in 2017, has an annual capture capacity of 1.4 Mt CO2. It is the world's largest CO2 capture facility at a coal plant. Installed on the 240 MW-W.A. Parish Unit 8, the capture facility is able to reduce CO2 emissions of the unit by 90%. The $1 billion project was built by US utility NRG and Japanese joint venture partner JX Nippon. CO2 is used for EOR at the nearby West Ranch oil field. The Japanese government provided a $250 million loan to the project. The project

18. Saskpower, "BD3 Status Update: March 2019", 12 April 2019, available at: www.saskpower.com.
19. International CCS Knowledge Centre (2018a), Summary for Decision Makers on Second Generation CCS, November 2018, available at: https://ccsknowledge.com.

also won a $190 million grant in 2010 from the US Department of Energy (DOE) Clean Coal Power Initiative. Petra Nova became operational on December 29, 2016, on budget and on schedule. Within the first 10 months, the plant delivered more than 1 Mt of CO2 and boosted oil production by 1,300%.[20]

While both projects use the **post-combustion technology**, they have different designs. Capture technology requires steam for amine regeneration. This steam can come from within the power plant (integrated design resulting in an electricity output penalty) or from an external dedicated steam supply (increased capital costs). The integrated approach was used in SaskPower's BD3, while the Petra Nova project opted for the second option.[21]

A third project, the 582-MW **Kemper County Energy Facility**, Mississippi, a planned integrated gasification combined-cycle (IGCC) plant fitted with carbon capture was stopped in 2017 and turned into a natural gas plant project in the wake of technical issues, delays and cost overruns attributed to the new coal gasification technology.[22] The project's costs steadily rose, topping $7.5 billion when factoring in mine, carbon dioxide pipeline, and other accounting costs.

Thus, among the three main approaches to capture CO2 from large-scale power plants (post-combustion capture, pre-combustion capture with gasification, and oxy-fuel combustion capture), only post-combustion has advanced so far.

There are only a limited number of new projects based on coal power.

In Canada, in July 2018, a decision was made not to retrofit **Boundary Dam units 4 and 5** with carbon capture technology, and instead to close them.[23] The historically low price of natural gas was as a significant factor in the decision, as well as the age of the units (built in the 1970s). No decision has been taken yet on the carbon capture retrofit of the 300-MW **Shand power station**, located near Estevan, Canada. A comprehensive feasibility study conducted by the International CCS Knowledge Centre has been carried out to examine whether carbon capture could work at the power station.[24] The study results show that significant

20. NRG, Petra Nova, available at: www.nrg.com.

21. International CCS Knowledge Centre (2018b), "New Heat Integration Strategy Improves the Efficiency of a CCS Facility", 24 August 2018, available at: https://ccsknowledge.com.

22. "Clean Coal's Flagship Project Has Failed", *MIT Technology Review*, 29 June 2017, available at: www.technologyreview.com.

23. CBC News, "SaskPower Abandons Carbon Capture at Boundary Dam 4 and 5", 9 July 2018, available at: www.cbc.ca.

24. International CCS Knowledge Centre (2018a), *op. cit.*

cost reductions can be achieved (see below). Should SaskPower decide to proceed, the project would produce the second, full-scale capture facility in Saskatchewan with a nominal capacity of 2 Mtpa.

In addition to the Canadian unit, among the 25 projects under construction and development in the world, **six projects (4 in China and 2 in South Korea) involve coal power plants**. Altogether, the CCS/CCUS projects based on coal power plants have a CO2 capture capacity of 12.4 Mtpa based on some 4 GW of coal capacity.

In China, efforts to develop CCUS are accelerating (see below), but the four projects based on coal power plants have been delayed. They were initially projected to be commissioned before 2020 and are now expected to be commissioned in the 2020s. The status of the two Korean projects is unclear. Both projects were launched in July 2010, when the Korean Government announced a national framework to develop CCS, with the aim of developing two commercial-scale plants by 2020. Now, the Global CCS Institute database indicates that the projects could be in operation in the 2020s. But in the meantime, South Korea's policy on coal generation has changed radically and the country may rather revitalize CCS/CCUS projects based on hydrogen.[25]

Table 2: CCS/CCUS projects in the coal power sector

Facility name	Status	Country	State / district	CO2 capture capacity (Mtpa)	Operation date	Capture type	Primary storage type
Boundary Dam CCS	Operating	Canada	Saskatchewan	1	2014	Post-combustion capture	EOR
Petra Nova Carbon Capture	Operating	United States	Texas	1.4	2017	Post-combustion capture	EOR
Shand CCS	Under evaluation	Canada	Saskatchewan	2	2020's	Post-combustion capture	EOR
China Resources Power (Haifeng) Integrated CCS Demonstration	Early development	China	Guangdong Province	1	2020's	Post-combustion capture	Dedicated geological storage - offshore deep saline formations
Huaneng GreenGen IGCC Project (Phase 3)	Early development	China	Tianjin	2	2020's	Pre-combustion capture (gasification)	EOR, dedicated geological storage options under review
Shanxi International Energy Group CCUS	Early development	China	Shanxi Province	2	2020's	Oxy-fuel combustion capture	Under evaluation
Sinopec Shengli Power Plant CCS	Early development	China	Shandong Province	1	2020's	Post-combustion capture	EOR
Korea-CCS 1	Early development	South Korea	Either Gangwon province or Chungnam Province	1	2020's	Post-combustion capture	Dedicated geological storage - offshore deep saline formations
Korea-CCS 2	Early development	South Korea	Not Decided	1	2020's	Pre-combustion or oxy-combustion	Dedicated geological storage - offshore deep saline formations

Source: Global CCS Institute, International CCS Knowledge Centre.

25. See: ekn, Jung Seung-il, "Become First Mover in the Hydrogen Industry", 18 January 2019 (in Korean), available at: www.ekn.kr.

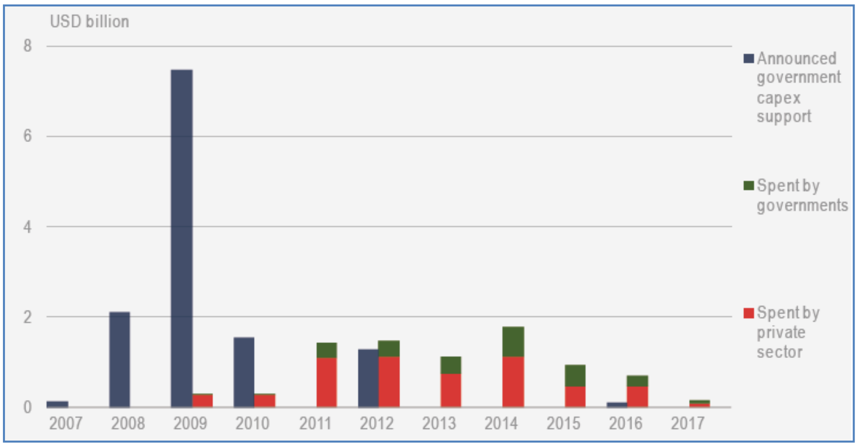
Barriers and challenges to CCS in the coal power sector

With only two large-scale operational plants in the world, CCS/CCUS in the power sector has encountered the same challenges than CCS/CCUS projects in other sectors: a lack of policy support, insufficient private and public funding; no or insufficient CO2 price. In addition, **CCS/CCUS deployment in the power sector is particularly challenging**, as the carbon capture technology incurs a significant capital cost and energy penalty, while energy revenues are increasingly limited by non-baseload operation.

The Global CCS Institute database has developed a Policy Indicator, which reveals that only six countries – Norway, the UK, the US, China, Canada and Japan – have established encouraging and progressive policies on CCS/CCUS. Governments have, overall, failed to implement policies that support a business case for investment and deliver policy confidence required to mobilise private capital.

CCS/CCUS has also suffered from a lack of public and private funding. According to the IEA, an estimated $10 billion in capital investment has been made in large-scale CCS/CCUS projects that are operating or under construction globally, most of it this decade.[26] This is in contrast to almost $2.3 trillion of investment in RES technologies made between 2010 and 2016. Investment in large-scale CCS/CCUS projects has declined markedly in recent years as government funding commitments for new projects have dried up.[27]

Graph 4: Investment in large-scale CCS/CCUS projects



Source: IEA World Energy Investment 2018.

26. IEA, "Five Keys to Unlock CCS Investment", 2017, available at: www.iea.org.
27. IEA (2018d), *World Energy Investment 2018*, July 2018, available at: https://webstore.iea.org.

One main impediment to CCS/CCUS in the power sector is the cost of capture. According to the Global CCS Institute, based on 'first-of-a-kind' technologies currently deployed at commercial scale, the addition of carbon capture equipment to unabated power facilities can result in **additional costs of 45% to 70% to the levelized unit cost of production**.[28] This is to be compared to an additional cost of as low as 2% for natural gas processing, 4% for fertiliser facilities and 5% for bio-ethanol production. The higher cost increase for power generation reflects that CO2 separation is not included in the process without carbon capture. Therefore, a greater incremental cost is incurred to separate CO2 when compared to the processes with inherent CO2 separation.

Adding a carbon capture facility requires investment in the order of $1 billion. This has made it difficult to secure from governments the amount of financial support necessary to get more early projects to happen.

The cost of CO2 capture has been estimated at **60$/t by the US** DOE, making it a costly option to retrofit existing coal power plants.[29] The IPCC notes that costs have not come down between 2005 and 2015 due to limited learning in commercial settings and increased energy and resources costs.

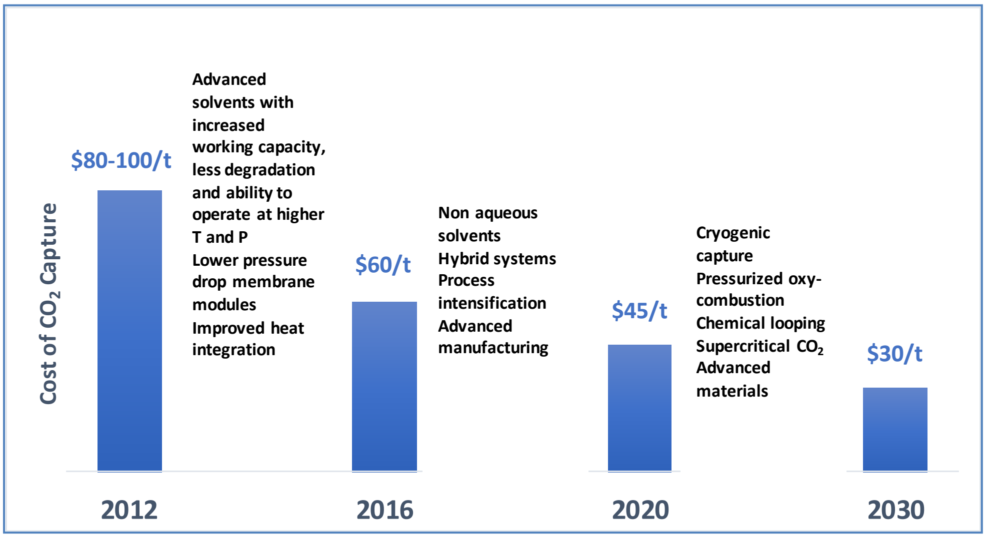
Separating CO2 from the other gases in a power plant's exhaust stream consumes a significant amount of the heat generated and reduces the electrical output from a power plant. This drop in the energy efficiency of the power plant due to carbon capture efforts is known as the **energy penalty**. The thermal efficiencies of power plants with carbon capture based on pulverised coal combustion with post combustion capture, oxy-combustion and IGCC with pre-combustion capture are 34.8 - 35.7% (low heating value - LHV basis), which is **around 9 percentage points lower** than a reference pulverised coal plant without capture.[30]

Learnings from the two retrofit plants in operation indicate that **substantive cost reductions are possible**. The US DOE has an R&D program conducting research and development activities on advanced carbon capture technologies that have the potential to provide step-change reductions in both cost and energy penalty as compared to currently available technologies. The program is targeting demonstration of second generation technologies that result in a captured cost of CO2 **less than**

28. Global CCS Institute (2017), *Global Costs of Carbon Capture and Storage – 2017 Update*, June 2017, available at: https://hub.globalccsinstitute.com.
29. US DOE (2018), "Fossil Energy's Carbon Capture Utilization and Storage Activities", November 2018, available at: https://static1.squarespace.com.
30. IEA Greenhouse Gas R&D Programme, "Costs of CO2 Capture Technologies in Coal Fired Power and Hydrogen Plant", 2014, available at: www.researchgate.net.

$40/t in the 2020-2025 timeframe and to approximately $30/t beyond 2030.[31] Innovation pathways include materials, processes and equipment.[32]

Graph 5: US DOE Cost of CO2 capture goals



Source: DOE.

NRG, the operator of the Petra Nova carbon capture-fitted power plant, indicates that this experience shows ways to cut costs up to 20% for the next generation of the technology, such as using smaller towers with less steel.[33]

Higher cost reductions have been highlighted by the analysis of the International CCS Knowledge Centre for the retrofit at Canada's Shand Power Plant, based on experiences from the operating capture project at BD3.[34] The Shand CCS Feasibility Study shows that there is a **67% reduction to capture plant capital costs** (on a cost per tonne of CO_2 basis). Based on the model, the levelized cost of captured CO2 is calculated at **$45/t**.

Factors such as scale, modularization, simplifications and other lessons learned as a result of building and operating the BD3 facility contributed directly to these reductions. Large cost reduction opportunities can be found through a process called **heat integration** and are broadly applicable to other industrial applications. Recycling heat can minimize the

31. US DOE Office of Fossil Fuel, "Carbon capture R&D", 2018, available at: www.energy.gov.
32. US DOE (2018), *ibid*.
33. Reuters, "U.S. Utilities Balk at Expanded Carbon-Capture Subsidy", 2 August 2018, available at: www.reuters.com.
34. International CCS Knowledge Centre (2018a), *op. cit.* and "Cost of Capturing CO2 Drops 67% for Next Gen Carbon Capture Plant", *Carbon Capture Journal*, January-February 2019.

amount of wasted heat, minimizing the amount of energy consumed and maximizing the amount of heat that is recovered during capture.

Modular construction was determined to be an ideal option for achieving cost reductions. Greater use of this modular approach presents an unparalleled opportunity for China's enormous fleet of similar coal units to draw on the economies of scale available in this approach.

The Shand CCS Feasibility Study has also studied how to **eliminate water requirements** for the capture facility. The CCS system was designed without the requirement for additional water. The proposed heat-rejection design would eliminate this burden by only requiring the use of water that has been condensed from the flue gas.

With increasing variable renewables in the power mix, the electricity system will need more **flexibility**. Although energy storage (in various forms) will make a significant contribution over time, variable renewable power currently requires a reliable electricity supply as back-up. In the future, carbon capture-fitted coal power plants will have to provide this function. There are no projects to date that provide experience of large-scale carbon capture-fitted coal plants operating flexibly. According to the IEA, retrofitting thermal power plants with one of the three main carbon capture routes appears to have only a small impact on their operational flexibility, provided that the capture systems are designed properly.[35] The technical difficulties of flexible operation of carbon capture-fitted plants are small compared with the economic consequences. Carbon capture-fitted plants are costly to build, and it is questionable whether newly built plants would be able to recover costs if required to operate flexibly. The Shand Feasibility Study has also explored this issue. According to the Study, a carbon capture-fitted power plant can be **designed for over-capture at reduced loads with no appreciable capital cost increases**, paving the way for these plants to integrate with renewables, resulting in a lower overall emission intensity. In the case of the Shand Study, it was possible to increase the capture rate from 90% at full load to more than 96% at the minimum turndown that could support variable renewables.

It remains that **changes in the power sector are a major impediment to carbon capture retrofits on coal power plants** as power utilities have to bear the risk of adding capture facilities to assets which may be hardly used in the future. The **merit order effect** may create uncertainties on the ability of the carbon capture-fitted plant to operate for long enough periods to cover the additional cost of generation

35. IEA (2018b), *op. cit.*

associated with carbon capture. As retrofits would have among the highest short-run marginal costs on the system, the plant's operating hours would be shorter in competitive markets in the absence of a high CO_2 price or some dispensation that guarantees that the plant is dispatched.[36] In regulated markets, individual plants might have more certainty about load factors. In these markets, regulators could balance investments in carbon capture facilities against the costs of an alternative portfolio of low-carbon generation, the legacy costs of phasing out coal assets more quickly and the value for the grid system of dispatchable carbon capture-fitted units.

The transport and injection/storage steps of the CCS process are not technologically challenging per se, as compared to the capture step. However, **the transport and injection steps still face challenges**, including economic and regulatory issues, rights-of-way, and questions regarding the permanence of CO_2 sequestration in deep geological reservoirs, as well as ownership and liability for the stored CO_2, among others.[37] In all cases, robust regulatory frameworks that clearly define the ownership of storage space, the holder of liability for stored CO_2 and how stored CO_2 will be treated under climate change legislation will be necessary to provide confidence in long term storage of CO_2 and make investments in storage projects bankable.[38]

According to the IPCC, storage capacity estimates vary greatly, but recent researches indicate that **10,000 GtCO2 could be stored in underground reservoirs**. Regional availability of this may not be sufficient, and it requires efforts to have this storage and the corresponding infrastructure available at the necessary rates and times. The initial development of dedicated CO_2 storage sites is a time-consuming and costly process, requiring detailed characterisation of possible reservoirs and drilling of exploratory wells. It is generally recognised that governments will need to play a major role in funding site characterisation, or alternatively, guaranteeing sufficient returns on investment.[39]

Finally, and fundamentally, there is the question of **social acceptance** of CO_2 storage locally, with the integrity of CCS, and the perceived risk of CO_2 leakage, being a concern. This may impede the storage of CO_2 in some countries as it has been observed in Europe for onshore CO_2 storage.

36. IEA (2018d), *op. cit*.
37. Congressional Research Service, "Carbon Capture and Sequestration (CCS) in the United States", 9 August 2018, available at: https://fas.org.
38. IEA (2018d), *op. cit*.
39. T. Lockwood, "Reducing China's Coal Power Emissions with CCUS Retrofits", IEA Clean Coal Centre, November 2018, available at: www.iea-coal.org.

While there are still many barriers to the deployment of CCS/CCUS in the coal power sector, learnings from the two retrofit plants in operation indicate that substantive cost reductions are possible, suggesting that CCS/CCUS could provide an important mitigation solution to CO_2 emissions of the existing coal fleet. The role of governments will be essential to make CCS/CCUS a viable option in the coal power sector. The next sections look at policy developments in the US and China.

Can CCS/CCUS Save US Coal Power Plants?

The US leadership in CCUS: New 45Q and other incentives

The US has a proven record and leadership in CCUS. Among the 18 large-scale CCS/CCUS projects operating in the world, 9 are in the US. Most of them, but the Petra Nova project,[40] have been developed for EOR. Over 23 Mt of CO2 are captured annually in the US from natural gas processing plants, refineries, and fertilizer plants and sold for EOR.[41] CO2-EOR has gained limited traction except in the US, which accounts for two thirds of global CO2-EOR production today, although even in the US it accounts for less than 3% of its total oil production.[42] More than 850 Mt of CO2 have been injected underground for EOR since 1972.[14] Most of it relies on natural sources of CO2 (which yields no emissions reductions benefits). The CO2-EOR industry has established a network that can transport and store CO2 over long distances. This provides a valuable platform for possible future use of CO2 captured from anthropogenic sources. While there are no current CCS/CCUS projects under construction in the US, **the new 45Q credit tax adopted in February 2018 is expected to spur a new wave of investment in CCS/CCUS projects.**

In February 2018, US Congress passed the Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions (FUTURE) Act, which expanded the **corporate income tax credit for CCS and CCUS**.[43] This tax credit, **known as 45Q**, was adopted to enable additional deployment of CCS/CCUS projects in the US. The new law raises the tax credit linearly from $22.66/t to $50/t over the period from 2017 until 2026 for CO2 captured and permanently stored, and from $12.83/t to $35/t over the same period for CO2 captured and used for EOR or other industrial uses of CO2. From 2027, the tax credit will be indexed to

40. The Petra Nova project also injects CO2 for EOR but its goal is to demonstrate post-combustion capture.

41. Clean Air Task Force (CATF) (2019), "Carbon Capture & Storage in The United States Power Sector - The Impact of 45Q Federal Tax Credits", February 2019, available at: www.catf.us.

42. IEA (2018b), *op. cit.*

43. Congressional Research Service, Carbon Capture and Sequestration (CCS) in the United States, 9 August 2018, available at: https://fas.org.

inflation. The cap on the credit that existed previously (75 Mt of qualified CO2 captured or injected) was removed, but the law requires that the credit be claimed over a 12-year period after operations begin. Additionally, to qualify, facilities must begin construction before 2024 and a minimum amount of CO2 is required to be captured and stored or utilized by the facility. This amount varies with the type of facility (0.5 Mtpa for power plants).

The new incentives are expected to provide a significant boost for CCS/CCUS investment. According to the IEA, the new law could trigger new capital investment on the order of $1 billion over the next six years, potentially adding 10 to 30 Mt or more of additional CO2 capture capacity.[44] Some stakeholders suggest that the changes to Section 45Q could be a "game changer" for CCS/CCUS developments in the US, incentivizing more development of large-scale CCS deployment like Petra Nova and Boundary Dam.[45]

In addition to 45Q, additional incentives at federal of state level are expected to give a boost to CCS/CCUS. Led by the US Carbon Capture Coalition,[46] and building on reform of 45Q, the Utilizing Significant Emissions through Innovative Technologies Act (**USEIT Act)** has been recently re-introduced in the Senate with bipartisan support (S.383) and is awaiting Senate passage.[47] If enacted, the USEIT Act would foster continued development and deployment of CCS/CCUS by authorizing the EPA Administrator to coordinate with the Secretary of Energy on furthering research, development and demonstration (RD&D) of carbon utilization and direct air capture technologies. The bill would also support collaboration between federal, state and non-governmental interests to **facilitate planning and deployment of pipelines to transport CO2 for ultimate storage or beneficial use** (amended FAST Act). To help financing CCS/CCUS projects, the Carbon Capture Coalition also supports federal legislation to make carbon capture projects eligible for **tax-exempt private activity bonds** (PABs) and **master limited partnerships**

44. IEA, "Commentary: US Budget Bill May Help Carbon Capture Get Back on Track", 12 March 2018, available at: www.iea.org.

45. Congressional Research Service, *op. cit.*

46. The Carbon Capture Coalition (CCC) is a nonpartisan coalition supporting the deployment and adoption of carbon capture technology. Its mission is to foster domestic energy production, support jobs and reduce emissions, all at the same time. See: http://carboncapturecoalition.org.

47. CCC, "The USEIT Act (Utilizing Significant Emissions through Innovative Technologies): Creating Economic, Jobs and Environmental Benefits through Carbon Capture and Utilization", available at: http://carboncapturecoalition.org.

(MLPs).[48] Members of Congress have already introduced legislation that, if enacted, would authorize these financial incentives.[49]

In addition to federal existing and proposed laws, **regulation at state level** will facilitate the development of CCS/CCUS projects. In September 2018, **California's low carbon fuels standard (LCFS) was amended with a protocol for CCS**.[50] The LCFS is the primary tool for California to reduce emissions from transportation fuels in the state. With this amendment, the **LCFS aims to achieve 20% reduction in carbon intensity of transportation fuels by 2030**, relative to 2011. Some of those reductions are allowed to come from the use of CCS technologies on industrial facilities. With the CCS Protocol, developers of CCS projects can access **an added incentive that tops up the 45Q tax credit**. The combination of the two incentives could help deploy CCS even more widely with a very attractive combined value of CO_2 at approximately $135 or $150/t, for EOR and saline storage respectively.[51] The Californian legislation is expected to benefit ethanol producers. With its first-class geology and its ambition to be a global climate action leader, California's initiative will facilitate the deployment of CCS in the transportation sector and of a networked infrastructure for CO_2 transport and storage.

The new federal and state incentives will trigger **investments in industrial facilities** with relatively pure CO_2 sources, such as ethanol plants, refineries, ammonia and methanol production. Two projects have already been announced, with more expected to follow. Occidental Petroleum and White Energy signalled their intention to work together to capture CO_2 from two White Energy **ethanol plants**. Separately, developers of the Lake Charles **Methanol plant** have plan to invest in a gasification facility expected to capture and store more than 4 Mt/y of CO_2.

According to a study done by **Princeton University** researchers, 45Q is expected to spur projects that would capture and store **30 Mt of CO_2 annually from ethanol refineries** within the next six years.[52]

48. PABs would allow developers of carbon capture projects access to tax-exempt debt to help finance their projects, thus lowering their capital costs. The MLP structure combines the tax benefits of a partnership with a corporation's ability to raise capital in public markets. Thus, allowing carbon capture projects to be MLPs would reduce the cost of equity and provide access to capital on more favourable terms.

49. Congressional Research Service, *op. cit*.

50. Clean Air Task Force (CATF), "California's CO2 Reduction Program Opens Doors to CCS", 10 November 2018, available at: www.catf.us.

51. CATF, 10 November 2018, *op. cit*.

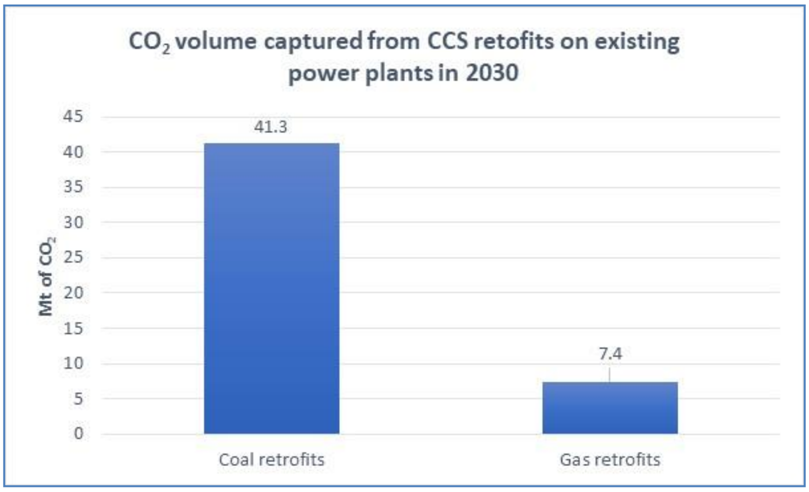
52. R. Edwards and M. Celia, "Infrastructure to Enable Deployment of Carbon Capture, Utilization, and Storage in the United States, Proceedings of the National Academy of Sciences", 18 September 2018, available at: www.pnas.org.

45Q alone unlikely to spur investment in the coal power sector

However, **there is no consensus on the impact of the new incentive on the coal power sector**.

A modelling analysis performed by Charles River Associates (CRA) for the Clean Air Task Force (CATF), has estimated **the impact of 45Q on CCS/CCUS deployment in the US power sector by 2030**.[53] The report concludes that 45Q has the potential to support deployment of CCUS in the US power sector. The modelling results leads to significant deployment of CCUS, capturing and storing approximately **49 Mt of CO2 annually in 2030**, from existing fossil fuel-fired power plants. Coal plant retrofits dominate capturing 41.3 Mt, while retrofits on natural gas combined cycle (NGCC) plants capture 7.4 Mt annually in 2030. The model shows that all these **retrofits rely on EOR revenue** to become economic. In other words, the model does not show any geological storage as a result of 45Q tax credits as EOR revenue is more favourable than the $50 tax credit for geological storage. In the model, CO2 is stored in three EOR basins, close to existing power plants: California, East & Central Texas and Mid-Continent and Permian Basins. In terms of installed power capacity, **the model partially retrofits 45 fossil-fired units, accounting for 20.4 GW of existing electricity generating capacity**. The carbon-controlled portion of this generating capacity is 10.8 GW with 8.03 GW of coal and 2.77 GW of NGCC.

Graph 6: Potential impact of US Q45 on existing power plants



Source: CATF.

53. Clean Air Task Force (CATF) (2019), *op. cit*.

The modelling results show that carbon capture-controlled electricity generation replaces uncontrolled fossil-fired power, not new or existing renewable energy. In terms of climate mitigation potential, the report concludes that Q45 offers a near-term pathway to meeting IEA's 2030 target for CO2 reduction through CCUS in the US power sector.[54] However, it also recognizes that to stay on track with meeting larger targets for 2050 and beyond, and attempting to not overshoot 1.5°C in global temperature rise, additional policy pathways – particularly at the state level – may be needed.

Another 2018 report funded jointly by Clear Path and the coal industry's Carbon Utilization Research Council concluded that, an **aggressive RD&D effort on CCUS could drive up to a 40% increase in US coal production for power from 2020 to 2040**; 100 million to 923 million barrels of additional domestic oil produced annually by 2040; 270,000 to 780,000 new jobs and an increase of $70 billion to $190 billion in annual GDP associated with EOR field operations by 2040.[55] By 2040, the study (using modelling provided by NERA Economic Consulting and Advanced Resources International) forecasts between 17 to 87 GW of coal and natural gas power plants with carbon capture.

On the contrary, the **EIA did not include the effects on the coal fleet of the 45Q federal tax credits** in its Annual Energy Outlook 2019. The EIA states that the credits, although doubled, still **do not appear large enough to encourage substantial market penetration of carbon capture in the scenarios modelled**.[56]

The report from Princetown University also concludes that carbon capture on industrial plants are favoured because of the high cost of capture in the power sector.[57] The report estimates the cost of capturing CO2 from coal or gas sources in a range of $50-75 /t, compared to around $20-30/t for ethanol sources, thus favouring industrial projects.

This is also the view of a recent report from the National Coal Council (NCC)—a federal advisory committee to the Secretary of Energy— which states that due to the age of the coal fleet and uncertainties on CCS/CCUS, some experts believe that in the absence of other incentives the amended 45Q is more likely to be used by industrial facilities with relatively pure CO2 sources.[58] However, the report does recognize that CCS/CCUS could play a

54. The comparison is done with IEA's 2DS model of 2017.

55. ClearPath and the Carbon Utilization Research Council, "Making Carbon a Commodity: the Potential of Carbon Capture RD&D", 25 July 2018, available at: www.curc.net.

56. EIA (2019b), *op. cit*.

57. R. Edwards and M. Celia, *op. cit*.

58. National Coal Council (NCC), *Power Reset – Optimizing the Existing U.S. Coal Fleet to Ensure a Reliable and Resilient Power Grid*, October 2018, available at: www.nationalcoalcouncil.org.

critical role in reducing the number of coal-based power plant shutdowns, by providing retrofit solutions with improved operational economics and near-zero emissions. However, the NCC also highlights that there is a need to lower costs for carbon capture or increase revenue from CO_2 sales to the point at which CCUS projects become profitable, which requires many more projects like the Petra Nova achieving technical advances through learning-by-doing, improved financing opportunities, etc.

Lack of interest from US power utilities

At the end of the day, power utilities will decide if they invest in carbon capture equipment. According to a Reuters survey carried out in August 2018, **of the top 10 US power companies, eight** (Duke Energy, Southern, Dominion, Exelon, Xcel, PG&E, Edison International and American Electric Power) **had no plans to purchase and install carbon capture equipment**, citing high costs and uncertain demand, while two (NextEra Energy Inc and PSEG) did not comment.[59] Three small utilities that industry watchers say are among the best-suited to adopt carbon capture technology because of their proximity to existing carbon pipelines and coal reserves - Rocky Mountain Power, Black Hills and OG&E - also told Reuters they had no plans to do so.

The power utilities say that although increased credits for CCS/CCUS are positive, the amount still **does not address the significant capital and operating costs**. They also estimate that it is unclear when or if revenues from CCS/CCUS would cover the required investment. Coal plants without carbon capture systems are having an increasingly difficult time competing with cheap natural gas, and wind and solar. Adding a $60/t cost for CO_2 capture, or even the $30/t cost targeted by the DOE by 2030, will further undermine coal's ability to compete.

The US utility industry is now moving quickly away from coal. CCS/CCUS investments looked potentially viable a decade ago when coal still generated half of US electricity but are being eclipsed today by **less-costly ways to produce electricity while curbing carbon emissions**.

In addition, the **US coal fleet is ageing**. More than half of the fleet is already more than 40 years old. Significant rebuilds would be required for plant owners to ensure that their facility could operate for the 20-30-year lifespan of any new carbon capture equipment. A 2012 global assessment of the viability and potential for retrofitting existing coal-fired power

59. Reuters, 2 August 2018, *op. cit*.

stations found only 4-25% of installed coal capacity in the US was potentially suitable for carbon capture retrofit.[60]

Political risks are another concern. President Donald Trump's successor could reverse efforts to support the coal industry, accelerating plant closures and making long-term carbon capture investments pointless.

Technology innovation may also further reinforce the trend towards natural gas at the expense of coal in the US. **An emissions-free natural gas power plant** began test operations in 2018, which has carbon capture built in as part of the combustion cycle aiming to compete with conventional combined cycle generation.[61] If proven in practice, this could be a game-changer, not only in the US.

No CCS retrofit on US coal power plants?

At least, **one investor has expressed interest in retrofitting a coal power plant with carbon capture.** In February 2019, New York-based hedge fund Acme Equities LLC announced its intention to take over New Mexico's **San Juan Generating Station (SJGS)**, targeted for closure by state lawmakers.[62] Acme Equities wants to retrofit the 46-year-old, coal-fired plant with carbon capture technology and sells the captured CO2 for EOR. Should the plant and the associated mine remain open,[63] it would allow Westmoreland Coal Company – which filed for bankruptcy protection in October 2018 - to continue supplying coal to the power plant. However, retrofitting such an ageing plant would require rebuild costs on top of the cost of the carbon capture equipment, which makes the project doubtful.

Absent a policy mandate for reducing CO2 emissions from the power sector, changes in gas prices, but also decreasing costs of renewable, and the age of the US coal fleet don't favour investment in retrofit of coal power plants, despite the positive signal of 45Q.

60. Center for International Environmental Law (CIEL), "Fuel to the Fire: How Geoengineering Threatens to Entrench Fossil Fuels and Accelerate the Climate Crisis", available at: www.ciel.org.
61. See NET Power: www.netpower.com.
62. Power mag, "Carbon Capture Proposed to Save New Mexico Coal Plant", 3 March 2019, available at: www.powermag.com.
63. "Impact Statement: San Juan Mine Could Stay Open until 2033", *Farmington Daily Times* 1 March 2019, available at: www.cfaenm.org.

When CCS/CCUS Based on Coal Power Takes Off in China?

China: an ideal laboratory for carbon capture retrofit of coal power plants

With above 1,000 GW of installed coal power capacity, China accounts for **half of the global coal fleet**. China's coal fleet is one of the youngest in the world, with 744 GW installed since 2006. This fleet is characterised by its high efficiency and is mainly constituted of large coal units of similar size. With its high proportion of large, efficient coal power units, **China offers an ideal case for minimizing carbon capture retrofit costs**, particularly with relatively low manufacturing costs and clear opportunities for mass production, modular construction and economies of scale.[64]

China is actively pushing for green and low-carbon energy development. As a clean and convenient energy carrier, electric power will gradually become the major energy type of final energy consumption, indicating that the decarbonization of power sector plays a vital part in achieving deep decarbonization pathway. In 2017, coal generation in China emitted 4.4 Gt of CO_2 or over **13% of global CO_2 emissions**. Reducing CO_2 emissions while expanding electricity use in China's growing economy is likely not achievable without **either a rapid decline in coal plant use and early retirement of many coal plants or carbon capture retrofits on coal power plants**. Despite the rapid deployment of clean energy, there is currently little prospect of early plant retirements in China, except for units below 300 MW that cannot meet environmental and saving standards. Therefore, **CCS/CCUS appears as a necessity for China** to realize the low-carbon transformation of its coal-based power system.

China's commitment to CCS/CCUS

China has long recognised the importance of CCS/CCUS. Since 2005, CCS has been listed as a frontier technology in China's mid/long-term technical development program in order to realize the goal of zero

64. T. Lockwood, "Reducing China's Coal Power Emissions with CCUS Retrofits", IEA Clean Coal Centre, November 2018, available at: www.iea-coal.org.

emissions from fossil fuel energy.[65] Since then, national public and private actors have funded research and industrial demonstration in many aspects, such as CCUS, oxygen-enriched combustion, pre- and post-combustion, high-purity CO_2 geological sequestration, EOR and enhanced coal bed methane recovery (ECBMR). Between 2005 and 2016, the Ministry of Science and Technology of China (MOST) and the National Natural Science Foundation of China (NSFC) funded 87 projects linked to CCS/CCUS.[66] Currently, several **pilot-scale and demonstration CCUS projects** collectively capture close to 1 Mtpa of CO_2.[67] More attention has been paid to CCUS, especially CO_2-EOR and CO_2-ECBMR to reduce the unit cost of projects, at least in the development stage of the technology. China's two major oil giants, China National Petroleum Corporation (CNPC) and China Petrochemical Corporation (Sinopec), have specialized research institutes engaged in related research work.

In 2013, China's main policy-making body, the National Development and Reform Commission (NDRC), adopted a new policy to promote the demonstration of **integrated CCUS projects** and pave the way for "large-scale application and commercialization".[68] The policy calls on local governments to take further steps on pilot projects along newly developed guidelines, which can improve research on capturing CO_2 as a way of addressing climate change and creating economic benefits. The new policy ensures that new research projects integrate all elements of the CCUS value chain, while previously, research projects separated the research for storing or utilizing CO_2 from the research for capturing CO_2. The new policy resulted in some provincial-level support for projects in Shaanxi and Guangdong provinces.

In 2015, the NDRC launched a **CCS Roadmap** managed by the Asian Development Bank (ADB).[69]

65. Geofluids, "Worldwide Status of CCUS Technologies and Their Development and Challenges in China", 2017(8): Article ID 6126505, August 2017, available at: www.researchgate.net.
66. Geofluids, *op. cit.*
67. Global CCS Institute (2018), *op. cit.*
68. World Resources Institute, "Recent Progress Shows China's Leadership on Carbon Capture and Storage", 22 October 2013, available at: www.wri.org.
69. Asian Development Bank, "Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China", 2015, available at: www.adb.org.

Box 1: Roadmap for Carbon Capture and Storage Demonstration and Deployment in China

The Roadmap was led by the Department of Climate Change of the NDRC, managed by the ADB, and co-financed by ADB's Carbon Capture and Storage Fund. It presents a **possible pathway with practical and specific policy actions to achieve zero-emissions from coal**. Its starting points are: 1) coal is expected to remain a dominant fuel in the foreseeable future in China, and 2) Carbon capture is currently the only available technology that can cut up to 90% of CO_2 emissions from large industrial processes and power plants based on coal and other fossil fuels. The Roadmap states that **without CCS/CCUS, the cost of meeting the country's anticipated long-term climate change mitigation objectives would be about 25% higher**. It considers that early demonstration of CCS/CCUS in China now will allow its timely and cost-effective deployment in the next 10–15 years.

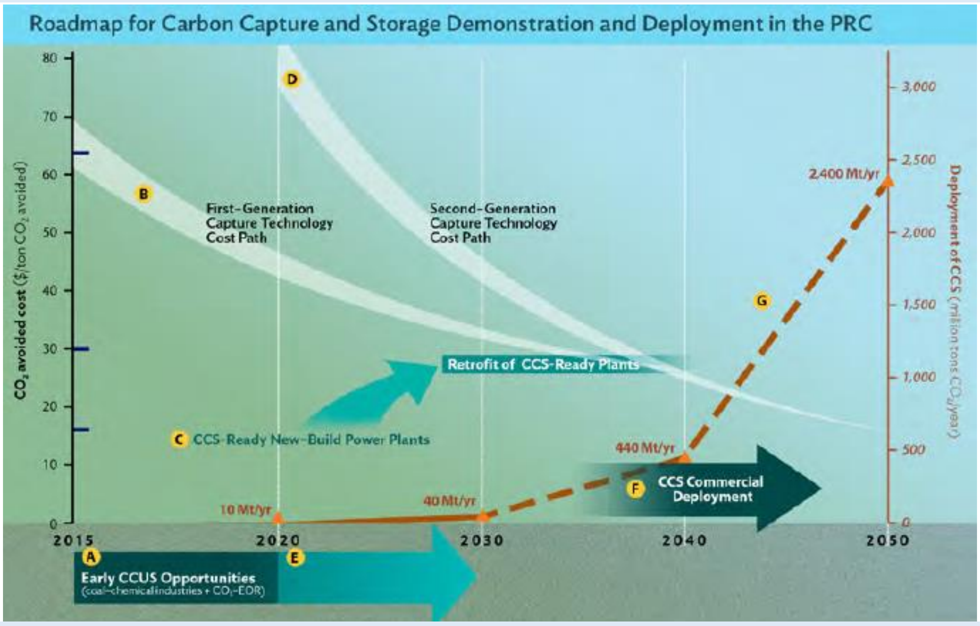
The Roadmap has identified unique low-cost opportunities for CCS/CCUS demonstration during the 13th Five-Year Plan (2016–2020), including Yanchang CCUS. But recognizing that **many crucial barriers remain to be overcome**, such as excessive energy penalty, high capital costs, perceived and real technical risks, weak CO_2 off-take agreement regime, it recommends a **phased approach** to overcome these early-stage challenges by **first targeting low-cost CCUS applications in coal–chemical plants with CO_2-EOR**. In parallel, intensive research and development activities including limited carbon capture application in coal-based power plants could bring down the capture costs, overcome energy penalty hurdles and provide new insights and experiences. This dual-track approach until the year 2025 can pave the way for wider deployment of cost-competitive CCS/CCUS from 2030 onward.

The Roadmap also recommends **improving the regulatory framework** for the second phase as well as **developing financial incentives** as CCS/CCUS demonstration faces formidable challenges in the absence of targeted support. Notably, for early-demonstration projects in the power sector, the government could establish a support program consisting of revenue support. Early-demonstration projects could be co-funded by the government, the industrial project owner, and international financial institutions, including ADB, and supported with revenue from auctions under the emerging national emission trading scheme.

The Roadmap projects commercial deployment of CCS/CCUS based on coal power plants starting after 2030. By 2050, 2.4 Gtpa of CO_2 could be captured in all sectors. The document states that the **projected CCS/CCUS deployment path is highly uncertain** and will depend on

(i) the degree of cost reduction achieved; (ii) the costs of CCS/CCUS relative to alternative low-carbon technologies, including nuclear and renewables; and (iii) gain in capture efficiencies.

Graph 7: Proposed CCS Roadmap for China



Source: ADB

In 2016, the government adopted two important plans for the development of CCUS: the **Energy technology innovation action plan** by the NDRC and the National Energy Administration (NEA) and the **13th Five-Year Plan for National Scientific and Technological Innovation** by MOST in August 2016.[70] The clean and high efficient use of coal has been included in the Science and Technology Innovation – 2030 Major Project, and a total of 22 demonstration projects (all technologies) have been arranged with a total funding of 164 billion yuan ($24 billion).[71] The major projects for clean and high efficient use of coal have four important goals and key research directions: first, accelerate the green production of coal (40% of the budget), second, efficient coal power generation (30%), third, clean coal conversion (20%), and fourth, CCUS (10%). The industry that conducts CCUS pilot projects involves the thermal power, coal chemical, cement and steel industries.

70. J. Ma, "China's CCUS Progress and Deployment", National & Local Joint Engineering Research Center of Carbon Capture and Storage Technology, Northwest University, 4 December 2017, available at: www.cslforum.org.

71. Carbon Road Information, "Where Is the Future of Coal Consumption?", 28 February 2019 (in Chinese), available at: https://ideacarbon.org.

In June 2017, **ADB signed a memorandum of understanding** with NDRC, Yanchang Petroleum Group, and Northwest University for a technical assistance grant of $5.5 million to develop a large-scale CCUS demonstration project.[72] Based on a pilot study that started in 2012, Shaanxi provincial government is developing the **Yanchang** CCUS project, a commercial scale demonstration project abating annually 1 Mt of CO2.

According to the Global CCS Institute, commitment to the technology is fast-growing as national, regional and municipal governments embrace CCUS and make it part of their long-term strategic plans.[73] There are now eight provinces that have included CCUS demonstration projects as a key technology for GHG reductions into their 13th Five-Year Plan.

The domestic CCUS industry has accelerated its development. In 2017-2018, China implemented a suite of measures designed to accelerate CCUS deployment. They include:

- Launching the national emission trading scheme (ETS) in the electricity sector (the market is in its preparatory stages and is now planned to come fully online in 2020) ;
- Widely promoting low-carbon technologies, with an emphasis on CCUS;
- Supporting CCUS pilots and Near Zero Carbon Emissions pilots;
- Providing grant funding for CCUS research projects promoted by MOST;
- Amending the Environmental Impact Assessment Guidelines to better address CCUS projects;
- Establishing a CCUS capacity building project for government officials.

Status of CCS/CCUS projects

Contrary to development in some regions, efforts to develop CCS/CCUS in China have been continuous since the middle of the 2000s and have accelerated recently. However, **CCS/CCUS in China is still in its infancy**. **The first large-scale** (as defined by the Global CCS Institute) **CCUS project was commissioned in 2018** when CNPC Jilin Oilfield CO2-EOR facility entered Phase III, reaching an injection capacity of 0.6 Mtpa. CO2 comes from natural gas processing. The project is the 18th large-scale CCS/CCUS project in operation in the world. It began research

72. Asian Development Bank (ADB), "PRC Agencies Sign $5.5 Million Grant to Pioneer Carbon Capture Project", 6 June 2017, available at: www.adb.org.

73. Global CCS Institute (2018), *op. cit.*

and development (Phase I) in 1990 and pilot and demonstration tests (Phase II) in 2008, reaching 1.12 Mt of cumulative injection in 2017.

In addition, there are currently two large-scale demonstration projects in construction in China, based on chemical production and associated with EOR operations (Sinopec Qilu Petrochemical CCUS facility and Yanchang CCUS project, see Table 2).

In addition, China has six large-scale projects (4 involving coal power plants) and 14 small-scale projects at an early development stage. **Current developments in CCUS therefore reflect the ADB Roadmap**, which envisaged a first phase of CCUS centred on coal-to-chemical facilities and EOR. The next phase with the large-scale demonstration of CCS/CCUS in the coal power sector remains to be carried out. There are currently **four large-scale projects involving coal power plants** expected to be commissioned in the 2020s (see Table 3). They involved the three capture technologies. They follow R&D efforts on capture technologies carried out since 2005. For instance, Huaneng Group took Beijing thermal power plant as a demonstration project of CO2 capture. Completed and put into operation in 2008, it successfully captured the CO2 with a purity of 98% and achieved over 85% recovery rate and 3000 tpa recovery amount. Huaneng Group also pushed forward the implementation of a CO2 capture demonstration project with a capacity of 100 ktpa at Shidongkou second power plant in Shanghai. Furthermore, Huaneng Group have pursued pre-combustion capture technology through its **GreenGen IGCC project**, which commissioned a 250 MW IGCC plant with a 100 ktpa capture unit in Tianjin in 2014, but has failed so far to progress to a planned larger unit (400 MW) incorporating CCUS.[74] Also, the **Carbon Capture Testing Platform of China Resources Haifeng Power** Plant ("Haifeng Project") was opened at the end of 2018 to test different capture technologies.[75] This marks the entry into the commissioning stage of Asia's first multi-threaded international carbon capture testing platform and the world's first carbon capture testing platform based on ultra-supercritical (USC) coal-fired generating units.

R&D of China's **geological storage resources** has mostly focussed on opportunities for EOR, but high-level characterisation and mapping of saline aquifer storage potential has also been conducted by the Chinese Academy of Sciences. Economically viable EOR storage capacity are estimated at **2.2 Gt**, whereas sub-basin evaluation of onshore saline

74. T. Lockwood, "Reducing China's Coal Power Emissions with CCUS Retrofits", IEA Clean Coal Centre, November 2018, available at: www.iea-coal.org.

75. GEDI, "Official Commissioning of Asia's First Coal-fired Power Plant Carbon Capture Testing Platform", 29 December 2018, available at: www.en.gedi.com.cn.

storage estimates around **746 Gt of CO_2** capacity associated with 'very highly suitable' sites (up to 1400 Gt in total), or almost 200 years of China's coal power emissions.[76] Injection into geological storage reservoir has been tested by Shenhua Group's (now CHN Energy) Ordos CCS Demonstration facility, which has injected approximately 300,000 tonnes of CO_2 over the period 2011–2014 into a dedicated geological storage reservoir.

Box 2: Chinese-European Emission-Reducing Solutions (CHEERS) project

Launched in October 2017, the Chinese-European Emission-Reducing Solutions, or CHEERS, involves a **second generation chemical-looping combustion (CLC) technology** tested and verified at laboratory scale (up to 150 kWth).[77] Within five years, the core technology will be developed into a 3 MWth system prototype for demonstration in an operational environment. The plant will be located at the technical center of Chinese thermal power equipment manufacturer Dongfang Boiler. It is anticipated that a successful demonstration will pave the ground for a wider deployment of the technology in the energy-intensive industry.

The innovation in this technology comes from the fact that oil and gas combustion produces relatively **pure CO_2**. Applied to industrial auxiliary systems, **CHEERS aims at reducing drastically the efficiency drop lost to the CO_2 capture chain**. Hence, a reduction by at least 50%, from a current level of 9-10%-points, typical of absorption techniques, to less than 4%-points in power generation systems seems feasible. In steam generation systems, the gain is even larger, dropping from a level of 18-33% efficiency penalty with absorption techniques to a mere 2-3%-points with the new technology. This gain will be demonstrated in operations using petroleum coke as the most challenging fuel.

In this respect, CHEERS is conceived as a greening measure for the petroleum refining sector, converting petroleum coke and heavy residual oil into auxiliary steam and power. The technology constitutes a major step towards large-scale decarbonisation of industry, offering a considerable potential for retrofitting industrial combustion processes.

The project has nine European and Chinese partners (Total, IFP Energies Nouvelles of France, Norway's SINTEF an independent Norwegian research organization, Silesian University of Technology in Poland, Norwegian non-profit Bellona, Tsinghua University, Beijing, Dongfang

76. IEA Clean Coal Centre, *op. cit*.
77. SINTEF, "Chinese-European Emission-Reducing Solutions – CHEERS", available at: www.sintef.no.

Boiler Group, Chengdu, Zhejiang University, Hangzhou and the China's Ministry of Science and Technology).

Still many challenges ahead

Despite these positive developments, CCS/CCUS in China still faces many challenges: a lack of policy operability; not enough commercial investment; and underdeveloped public participation.[78] **China still lacks a regulatory framework for CCS/CCUS and storage of CO_2 (beyond EOR-based storage) and financial incentives for projects**, two crucial pieces for any future CCS/CCUS deployment. Despite constant efforts to develop the technology, CCS/CCUS projects in China are small-scale and significant barriers to large-scale demonstration exist.

EOR is a major focus of CCUS in China. EOR can facilitate oil and CBM production in China and therefore has a strategic dimension in China. But compared with the status of CO_2-EOR technology in the US, extensive application of CO_2-EOR in most oilfields of China may be difficult as the geologic structure of most reservoirs is characterized by many faults and low permeability.[79] In addition, although an important driver for early CCUS deployment and infrastructure development, EOR may not provide a long-term incentive for coal power-based projects, due to limited demand and competition from other emitters with lower capture costs.[80]

As for the majority of CCS/CCUS projects operating worldwide, Chinese projects mostly **focus on sectors offering high stream of CO_2** and lower capture costs (e.g. coal-to-chemicals). Currently, only four large-scale CCS/CCUS projects are based on coal power plants. The main issues in the sector are similar to the global experience: i) the **high cost of the capture plant**, especially in the Chinese context where the capital cost of capture retrofit can be equivalent to the cost of the power plant itself, and ii) **the energy penalty** which reduces the efficiency of the plant.

Furthermore, **a shared infrastructure for CO_2 transport and storage needs to be developed**. Unlike the US, **there is no CO_2 pipeline network in China**; most captured CO_2 is transported by tanker trucks. The construction of CO_2 pipelines is just starting and the cost of building such pipelines is much higher than in the US. Although

78. Global CCS Institute (2018), *op. cit.*

79. Geofluids, *op. cit.*

80. IEA Clean Coal Centre, *op. cit.*

possible storage sites in the vicinity of the emission sources has been mapped, further exploration work on promising storage sites has to be carried out to identify their properties (permeability, porosity, etc.) and their adequacy for permanent CO2 storage. Certainty on storage potential and feasibility of CO2-EOR also requires more detailed and cost-intensive storage site assessment.

The building of the **transport and storage infrastructure** is a complex and costly undertaking, that would require substantial funding, and the implementation of a regulatory framework to manage long-term environmental liabilities.

Costs will determine whether it is attractive to retrofit a coal-fired power plant in China with carbon capture. Currently it is a major impediment to apply CCS/CCUS in the coal power sector.

A 2018 report by the IEA Clean Coal Centre has assessed the cost for retrofitting a generic 1,000 MW ultra-supercritical unit with post combustion capture in the period 2025 to 2030, as well as potential incentives that could facilitate deployment. The analysis assumes a baseline capacity factor for the retrofitted power plant of 75%, assuming a degree of priority dispatch for a low-carbon, dispatchable generator. The analysis finds the electricity tariff required to enter profitability is 450 yuan/MWh ($68/MWh) at a CO2 price of zero, which is well below the tariffs currently available for existing RES developments (but well above the current benchmark tariff for coal power (about 320 yuan/MWh in 2018) which does not internalize environmental costs). Even lower tariffs of below 400 yuan/MWh ($60/MWh) may be viable should the national CO2 price reach 100 yuan/t ($15/t), the level projected by analysts by 2025, representing a 25% increase on current average tariffs for coal power. For projects in suitable locations, sale of a portion of CO2 for EOR can act as a key supplement to these incentives, placing a higher value on CO2 (around 200 yuan/t ($30/t)) and providing a bankable revenue stream. The report concludes that **with appropriate policy actions commensurate with the support provided for other low-carbon technologies, application of CCS/CCUS to China's largest coal units can become a commercially viable prospect for power companies in 2025.**

Access to storage will be an important factor for carbon capture retrofit. An IEA analysis in 2016 identified about 385 GW of China's coal-fired capacity with suitable CO2 storage within a 250 km radius.[81] In total, about 310 GW of existing coal-fired power capacity met a number of basic criteria for being suitable for a retrofit (size, load factors and proximity to a high-quality storage resource), including 100 GW at a cost of under $50/MWh, which would need to be covered by some form of market mechanism or subsidy. But the IEA Clean Coal Centre indicates that in the densely populated southern coast of China (Guangxi, Guangdong, and Fujian provinces), where many large power plants are found, there is no onshore storage within a reasonable pipeline distance.[82]

No clear direction yet

To meet its NDC in line with the Paris Climate Agreement of 2015, China has committed to peak its CO2 emissions by 2030 or earlier and, by the same year, to reduce its carbon intensity by 60%-65% from its 2005 levels, and to increase the share of non-fossil fuel consumption in total primary energy consumption to 20%. China is one of the few countries that have included CCS/CCUS in its NDC (with a focus on continuous R&D efforts). China is on track to meet its 2030 NDC and **CCS/CCUS technology is not required to achieve China's key commitment to peak CO2 emissions by 2030,** provided China goes on with its coal control policy. Thus, high-level political support for pushing CCS/CCUS deployment in the coal power sector beyond a small number of demonstration projects in this period appears to be uncertain.

The attitude of coal power utilities towards future CCS/CCUS development pace is cautious. So far, they have shown little appetite for investment in carbon capture, but they maintain a level of technological capacity. Concerns stem from the technology's maturity and cost, as well as the worrying prospect of coal power.[83] Since renewables have been rapidly deployed and their cost reduced, the coal power sector is facing increasing competition. In recent years, the annual operating hours of coal power have significantly declined. In addition, faced with higher coal prices, power utilities are facing financial difficulties as they are not able to pass that cost on to the consumer. Under these conditions, and without policy incentives, there is no economic business case to retrofit coal power plants with carbon capture.

81. IEA, "Ready for CCS retrofit: The Potential for Equipping China's Existing Coal Fleet with Carbon Capture and Storage", *Insight Series*, 2016, available at: www.iea.org.

82. IEA Clean Coal Centre, *op. cit.*

83. L. Jiaqiao *et al.*, "Coal Power Sector in China, Japan and South Korea: Current Status and the Way Forward for a Cleaner Energy System", 2018, available at: www.kikonet.org.

The challenging CO_2 emissions standard of 550g/kWh by the end of 2020, set for large power generation enterprises could, in principle, be an important driver for retrofitting carbon capture (or partial carbon capture) to a proportion of the companies' coal fleets. However, some power companies have indicated that they will not look to employ CCS/CCUS to meet the target, but pursue other options, such as grouping with hydro power companies to improve the average intensity.[84]

The new national ETS may provide an opportunity to deploy CCS/CCUS. However, it is still under development and the mid-term projection of the carbon price ($15/t in 2025) may not be sufficient alone to drive CCS/CCUS in the coal power sector, which would require a minimum CO_2 price of $30/t to breakeven, according to the IEA Coal Centre. As CO_2 prices rise in the future, the national ETS could effectively provide economic incentives to retrofit coal power plants.

Overall, in the period to 2025/30, **government support is necessary to encourage the deployment of carbon capture technologies in the power sector. So far, such support is missing.** In addition, CCS/CCUS in China entails logistic challenges as the transport and storage infrastructure has to be created.

China is on track to meet its 2030 NDC. Yet Chinese NDC is not sufficient to achieve the goal of below 2°C, let alone 1.5°C.[85] China is currently formulating a longer-term plan for GHG reductions until 2050, which is expected to inform future international commitments. It is also expected to give direction on the role of CCS/CCUS. This role will depend on the **outcome of a least cost decarbonization pathway**, taking into account the costs of an alternative portfolio of zero-carbon generation, the legacy costs of phasing out coal assets more quickly and the value for the grid system of dispatchable carbon capture-fitted coal units. Obviously, this role will also depend on carbon capture reduction costs. China's decision to start promoting large-scale, integrated CCS/CCUS projects could usher in significant decreases in carbon capture costs through learning-by-doing and identifying cost-effective ways of operating.

84. IEA Clean Coal Centre, *op. cit.*
85. Climate Action Tracker, "China", 30 November 2018, available at: https://climateactiontracker.org.

Conclusion

There is global momentum to drive CCS/CCUS forward and growing policy support. However, most existing projects capture CO2 from natural gas processing or other industrial processes and are in the US or Canada. This is partially due to using captured CO2 to enhance oil recovery, which offers an additional revenue. New projects, as well as operating projects outside North America, focus on industrial applications and decarbonized hydrogen.

The contribution of CCUS to decarbonising the coal power sector has advanced with the recent commissioning of two coal units fitted with carbon capture in North America. However, it remains minimal. The seven large-scale projects based on coal power plants are still under evaluation and their implementation remains uncertain. Similar to experiences in the 2000s, capital cost of carbon capture and energy penalty remain major impediments to CCS/CCUS deployment in the coal power sector. Learning from the two retrofit plants in operation indicate that substantive cost reductions (up to 67%) are possible, suggesting that CCS/CCUS could provide an important mitigation solution to CO2 emissions of the existing coal fleet.

However, since the 2000s, the global electricity markets have changed profoundly and structurally. A key driver is the fast deployment of RES and their falling costs, making renewables increasingly competitive with coal (but their value for the grid system differ). Coal is also becoming less competitive than other sources of electricity in several regions, due to the fall in gas prices, the rising cost of the carbon price and higher coal import prices. The developed nations are focusing their decarbonization efforts on shifting the electricity mix away from coal, primarily due to abundant availability of cost-competitive (and often subsidized) alternative fuels. The window for retrofitting carbon capture to coal power plants is closing rapidly in developed nations due to the shift away from coal. In the US, cheap natural gas, rising renewable deployment and the ageing coal fleet deter investment in carbon capture facilities on coal power plants.

In emerging Asia, and notably in China, due to the large and young coal fleet, deployment of CCS/CCUS on the coal fleet appears today the only solution to reduce CO2 emissions of the power system in the long term, while ensuring reliability and security of electricity supplies and avoiding coal plants to become stranded assets. However, the necessary investment has been lagging, because of the cost of carbon capture and energy penalty, lack of policy support and uncompleted regulatory framework. The lack of opportunities to use captured CO_2 in oil fields has also be an impediment to the deployment of carbon capture on coal power plants. Implementing CCS in emerging Asia would require the development of carbon transport and storage infrastructure. This is a complex and costly undertaking, that would require substantial funding, and the implementation of a regulatory framework to manage long-term environmental liabilities. Recent policies in the power sector in China show a rapid trend towards clean generation (renewables, nuclear and some gas), a cap on coal capacity (although with some uncertainties on the cap level), aggressive development of flexibility tools (energy storage, demand side management and smart grids), and great plans and investments to interconnect the electricity grid at national, regional and international levels. Apart from continuous R&D efforts and deployment of small-scale demonstrators, there is not yet any commitment to CCS/CCUS in the coal power sector in China. If CCS/CCUS is to be part of the mitigation solutions, efforts to make the technology commercially viable need to step up and the regulatory framework needs to be enhanced.

Finally, as the focus of global projects is more and more towards utilisation of CO_2, R&D efforts in CO_2 utilisations must be reinforced. The application of innovative technologies, for instance in the provision of an alternative raw material base for the chemical industry, is a promising approach.

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