circular carbon economy

06

Remove: Carbon capture and storage.

GLOBAL CCS INSTITUTE

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Reduce. Reuse. Recycle. **Remove.**

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Executive summary

The mathematics of climate change are unforgiving. It reduces to a deceptively simple equation which when solved, leads to a clear conclusion that net-zero emissions energy and industry is necessary to meet climate targets. Despite more than two decades of international negotiations and trillions of dollars spent on research and subsidies, unabated fossil fuels still provide about 80% of primary energy and global emissions of CO_2 continue to grow. The gap between what is required to stabilise the global climate and what is required to maintain and grow modern economies has never been wider. Demand for energy, cement, steel, fertilizer, plastics and many other materials and chemicals that form the building blocks of modernity will be higher in 2050 than today. That demand is driven by two billion extra people to feed, clothe, house, transport and entertain, hundreds of millions of which will have become sufficiently affluent to consume these emission intense goods and services for the first time.

It is time to recognize that a more progressive approach to climate change is necessary. The old thinking, rooted in the belief that the two silver bullets of renewable energy and energy efficiency would deliver rapid emission reductions must be replaced with new thinking that embraces every feasible option and sets a path to net-zero emissions. The concept of a circular economy with its "three Rs" of Reduce, Reuse and Recycle, works well in describing an approach to sustainability considering the efficient utilization of resources and wastes, but has proven manifestly inadequate as a framework for defining climate action. To be effective, a fourth R must be added; Remove, creating a new concept – the Circular Carbon Economy (CCE). The CCE provides for the removal of carbon dioxide from the atmosphere (Carbon Direct Removal or CDR) and the prevention of carbon dioxide, once produced, from entering the atmosphere using carbon capture and storage (CCS). The CCE establishes a framework that respects the analysis of the Intergovernmental Panel on Climate Change (IPCC) and many others, that all conclude that CCS and CDR, alongside all other options, are essential to achieve climate targets.

CCS describes a family of technologies that capture CO_2 from large point sources such as industrial facilities or power stations, compresses the CO_2 to a supercritical fluid, and injects it into suitable geological structures 800 meters or more beneath the earth's surface for permanent storage. At those depths, the CO_2 remains a supercritical fluid, with a density similar to water.

These technologies are not new. The first CO_2 capture processes were commercialized in natural gas processing almost 90 years ago. Geological storage of CO_2, in the course of Enhanced Oil Recovery, commenced almost 50 years ago. Continuous dedicated geological storage of CO_2 commenced more than 20 years ago. Today, 21 commercial CCS facilities with a total capacity of 40Mtpa CO_2 are operating, three more are in construction, 16 are in advanced development and approximately another 20 are in early development. Each of these facilities is or will permanently store hundreds of thousands of tonnes of CO_2 per year, and several store more than one million tonnes of CO_2 each year, captured from power and industrial facilities. To date, approximately 260Mt of anthropogenic carbon dioxide has been safely and permanently stored in geological formations.

They also continue to improve, as expected for any industrial technology. The cost of capturing CO_2 from power stations has halved over the past decade and the next generation of capture technologies offer further reductions in cost. The lowest cost opportunities for CCS can deliver multi-million tonne CO_2 abatement at a single facility, at a cost of less than USD20 per tonne.

In addition to capturing CO_2 at its source, CO_2 must be removed from the atmosphere to achieve climate targets. The capture of CO_2 from the utilization of biomass, and directly from the atmosphere followed by permanent geological storage (BECCS and Direct Air Capture with storage: DACS) are important negative emission technologies offering higher security and greater flexibility than nature-based solutions, which are also essential.

CCS encompasses a versatile suite of technologies that can be applied to almost any source of carbon dioxide. It is this versatility that underpins its enormous carbon management potential. The IPCC's Special Report on Global Warming of 1.5 Degrees Celsius published in 2018 reviewed 90 scenarios, almost all of which required CCS to limit global warming to 1.5 degrees Celsius. The average mass of CO_2 permanently stored in the year 2050 across all scenarios reviewed by the IPCC report was 10Gt. The IPCC constructed four illustrative pathways to represent the range of 1.5 degree scenarios in the models it reviewed. Three of the four illustrative pathways required CCS with cumulative CO_2 storage to the year 2100 of between 348Gt and 1,218Gt. The fourth illustrative pathway required final energy demand to reduce by one third by 2050 compared to 2010. The lowest risk pathway probably lies somewhere in the middle. In any case, it is clear that CCS has a carbon management potential this century of hundreds to thousands of billions of tonnes of carbon dioxide.

However, like renewable energy, nuclear power and many other essential technologies, CCS is not being deployed at the rate and scale necessary to achieve climate targets. The reason is that the incentive for investment in CCS is generally insufficient to mobilize the requisite capital. There are several market failures across the CCS value chain that directly affect the business case for CCS. For a potential capture plant developer, the main impediment to investment is the lack of a sufficient value on emissions reductions. Without this, there is no incentive for a developer to incur the costs of constructing and operating the capture plant, even though it may be beneficial from a broader societal perspective in helping to meet climate targets cost effectively. In economic terms, CO_2 emissions are an externality.

Even where there is a value on emissions reductions, financiers and investors perceive CCS as risky, due to a range of factors mostly related to the immaturity of the CCS industry. The business norms that reduce perceived risk in mature industries have not yet developed for CCS and the result is a risk premium that is applied to the cost of capital undermining the investability of projects.

Capital intensive investments like CCS are exposed to many classes of risk. Most of these risks are best managed by the value chain actors. However there are also 'hard to manage' risks that the private sector is unwilling or unable to take on at an appropriate price. These risks are usually managed through government policy and regulation. For example, corporate law provides a general framework for undertaking business that significantly reduces the risk of undetected dishonest behavior by counterparties. For CCS, there are three specific hard to manage risks:

- Policy and revenue risk
- Cross chain risk
- CO_2 storage liability risk

All things considered, it is clear that the primary barrier to the deployment of CCS at the rate and scale necessary to achieve climate targets is the difficulty in developing a project that delivers a sufficiently high risk-weighted return on investment to attract private capital.

In order to deliver the public good of a stable climate, governments should introduce policies and make investments that incentivize private sector investment in CCS, and all other low emission technologies. Government alone will not solve the challenge of climate change. The solutions (and there are many) will be developed, commercialised and deployed by the private sector which has enormous resources and capabilities. All that is required are the incentives to mobilise private capital, and the creation of those incentives is entirely within the purview of government.

Recommendations for government

Recommendation 1. Based on rigorous analysis define the role of CCS in meeting national emission reduction targets and communicate this to industry and the public.

Recommendation 2. Create a certain, long term, high value on the storage of CO_2.

Recommendation 3. Support the identification and appraisal of geological storage resources – leverage any existing data collected for hydrocarbon exploration.

Recommendation 4. Develop and promulgate specific CCS laws and regulations that:

- establish clear processes for project developers to secure the right to exploit geological storage resources
- allow developers to effectively manage compliance risk associated with CO_2 storage operations, and
- provides for the commercially acceptable management of long-term liability for stored CO_2.

Recommendation 5. Identify opportunities for CCS hubs and facilitate their establishment. Consider being the first investor in CO_2 transport and storage infrastructure to service the first hubs.

Recommendation 6. Provide low cost finance and/or guarantees or take equity to reduce the cost of capital for CCS investments.

Recommendation 7. Where necessary, provide material capital grants to CCS projects/hubs to initiate private investment.

01
Introduction

Introduction

The Challenge of Achieving Net-Zero Emissions

Preventing dangerous interference with the global climate system will require anthropogenic greenhouse gas emissions to reach net-zero in the second half of this century. This means arriving at a steady state equilibrium in carbon cycles by either having no more anthropogenic emissions, or having any emissions balanced by corresponding removals of greenhouse gases from the atmosphere by enhanced sinks. This must occur against the backdrop of a rising human population and increasing affluence, especially in developing economies which are delivering a rapid rise in Gross Domestic Product (GDP) per capita. In summary, there will be more people with a significantly greater average economic capacity to consume goods and services.

The Japanese economist Yoichi Kaya describes the relationship between CO_2 emissions, population, energy use and GDP in his famous equation known as the Kaya identity.[1]

$$F = P \cdot \frac{G}{P} \cdot \frac{E}{G} \cdot \frac{F}{E}$$

Where:
F = global CO_2 emissions from human use of energy
P = global population
G = global GDP
E = global consumption of energy

The identity shows that CO_2 emissions are proportional to population (P), GDP per capita (G/P), the energy intensity of the global economy (E/G) and the emissions intensity of the global energy system (F/E). Adopting assumptions used by the International Energy Agency,[2] global population will grow from 7.6 billion in 2018 to 9.2 billion by 2040, global GDP will grow at a compound average annual rate of 3.4% to 2040 and energy efficiency (E/G) will improve by 2.3% per year. Substituting these values into the Kaya Identity shows that global anthropogenic emissions could be 51% higher in 2040 compared to 2018 if the emissions intensity of energy remains unchanged. This demonstrates the criticality of developing a near-zero emissions global energy system as the emissions intensity of energy is the only variable left to proactive intervention. Whilst the emissions intensity of the global energy system is already falling, it will not achieve near-zero status without strong policy action that takes advantage of every opportunity to reduce emissions.

[1] Kaya, Yoichi; Yokoburi, Keiichi (1997). Environment, energy, and economy : strategies for sustainability. Tokyo [u.a.]: United Nations Univ. Press. ISBN 9280809113.

[2] IEA (2019) World Energy Outlook 2019, Stated Polices Scenario.

A More Progressive Approach is Necessary

A framework that is inclusive of all carbon mitigation options is required to avoid the trap of sub-optimisation, where a system yields less than the best possible outcome due to poor coordination between its different component parts. In the context of achieving net-zero emissions, focusing on a subset of the available opportunities and failing to apply sufficient resources to others is a textbook example of sub-optimisation. The Circular Carbon Economy (CCE) concept developed by the King Abdullah Petroleum Studies and Research Center (KAPSARC) helps to address this risk by creating a framework that recognizes and values all emission reduction options.[3] The CCE builds upon the well-established Circular Economy concept, which consists of the "three Rs" which are Reduce, Reuse and Recycle. The Circular Economy is effective in describing an approach to sustainability considering the efficient utilization of resources and wastes however it is not sufficient to describe a wholistic approach to mitigating carbon dioxide emissions. This is because it does not explicitly make provision for the removal of carbon dioxide from the atmosphere (Carbon Direct Removal or CDR) or the prevention of carbon dioxide, once produced, from entering the atmosphere using carbon capture and storage (CCS). Rigorous analysis by the Intergovernmental Panel on Climate Change, the International Energy Agency, and many others all conclude that CCS and CDR are essential to achieve climate targets.

An approach that is more progressive than the Circular Economy is required for climate action. To that end, the Circular Carbon Economy adds a fourth "R" to the "three Rs" of the Circular Economy; Remove. Remove includes measures which remove CO_2 from atmosphere or prevent it from entering the atmosphere after it has been produced such as carbon capture and storage (CCS) at industrial and energy facilities, bio-energy with CCS (BECCS), Direct Air Capture (DAC) with geological storage, and afforestation.

Measures taken under the Remove dimension of the Circular Carbon Economy contribute to climate mitigation by storing carbon dioxide in the geosphere (CCS or DAC with geological storage) or in the biosphere (nature-based solutions such as afforestation). However, CO_2 stored in the biosphere via nature-based solutions may be susceptible to release due to natural phenomena such as fires, droughts or disease (of plants). Technology-based solutions such as CCS and DAC with geological storage offer extremely secure and permanent storage of CO_2 , which is not susceptible to disruption from fire or weather, as well as requiring very little land for facilities with a capacity to provide multi mega-tonne per annum abatement.

[3] KAPSARC (2019). Instant Insight, November 06, 2019. Achieving Climate Goals by Closing the Loop in a Circular Carbon Economy.

Both nature-based and technology-based solutions are essential elements of a comprehensive approach to driving CO_2 emissions towards net-zero. The critical requirement for success in achieving climate targets is that both technology-based and nature-based solutions under the Remove dimension, along with all other options under the other “three Rs” of the Circular Carbon Economy, are available for selection and that incentives for investment enable deployment of the best option in each circumstance, whatever that may be.

02
Current status of CCS

Current status of CCS

Introduction to Carbon Capture and Storage

CCS describes a family of technologies that capture CO_2 from large point sources such as industrial facilities or power stations, compresses the CO_2 to a supercritical fluid, and injects it into suitable geological structures 800 meters or more beneath the Earth's surface for permanent storage. At those depths, the CO_2 will remain a supercritical fluid, with a density similar to water.

The capture of CO_2 from gas streams is not new. CO_2 capture technologies based on chemical solvents (amines) were first commercially deployed in the 1930s to separate CO_2 and other acid gases from methane in natural gas production. Prior to 1972, all CO_2 captured was vented to atmosphere except a small proportion used or sold for other purposes such as urea production or beverage carbonation.

The first commercial CCS facility commenced operation in 1972 at the Val Verde Natural Gas Plant in west Texas USA. This facility is still operating as the Terrell gas processing facility. CO_2 captured from natural gas processing at Terrell is transported via a pipeline to oil fields where it is injected for Enhanced Oil Recovery (EOR). In EOR, the injected CO_2 mixes with the oil reducing its viscosity resulting in greater recovery of oil in place. Generally, approximately half of each tonne of CO_2 injected becomes permanently trapped in the pore space originally occupied by the oil and the other half is produced with the oil. At the surface it is separated from the oil and then re-injected, together with additional CO_2 to make up the difference for that which has become permanently stored. Ultimately, all the CO_2 injected becomes permanently trapped in the pore space previously occupied by the oil.

More generally, any rock formation of sufficient size and depth with adequate porosity and permeability is a potential CO_2 storage reservoir if migration of CO_2 to the surface is prevented by other impermeable rock formations. Geological storage of CO_2 utilises the same forces and processes that have trapped oil, gas and other hydrocarbons in the subsurface for millions of years. Global geological storage capacity is conservatively estimated to exceed 4000 billion tonnes of CO_2, which is more than sufficient for CCS to play its full role in emission mitigation under any scenario. The overwhelming majority of that potential storage capacity is not associated with oil or gas production, but rather with formations currently saturated with saline water.

The behaviour of fluids like CO_2 in the subsurface is very well understood courtesy of more than a century of experience in the oil and gas industry and a large body of more recent academic research and monitoring. The probability of leakage of CO_2 to the atmosphere from an appropriately selected and operated geological storage reservoir is diminishingly small. For example, in an article published in Nature Communications in 2018, Alcade et al concluded that there was 50% probability that more than 98% of CO_2 injected would remain trapped after 10,000 years for a well-regulated CCS industry. Alcade also considered an unrealistic scenario where regulation was inadequate and injection was conducted in a region with a high risk of leakage and improperly closed abandoned wells. Even under these worst-case conditions, Alcade concluded that more than 78% of the CO_2 injected would remain trapped in the subsurface over 10,000 years.[4] To date, approximately 260Mt of anthropogenic carbon dioxide has been safely and permanently stored in geological formations.[5]

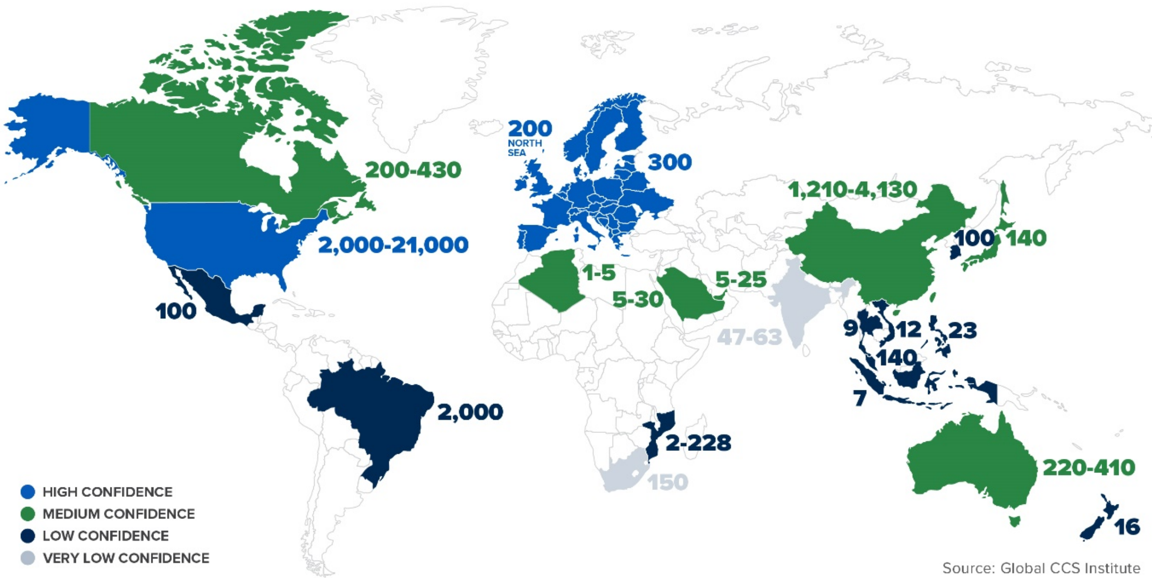


Figure 1. Estimated CO_2 Geological storage capacity – billions of tonnes.

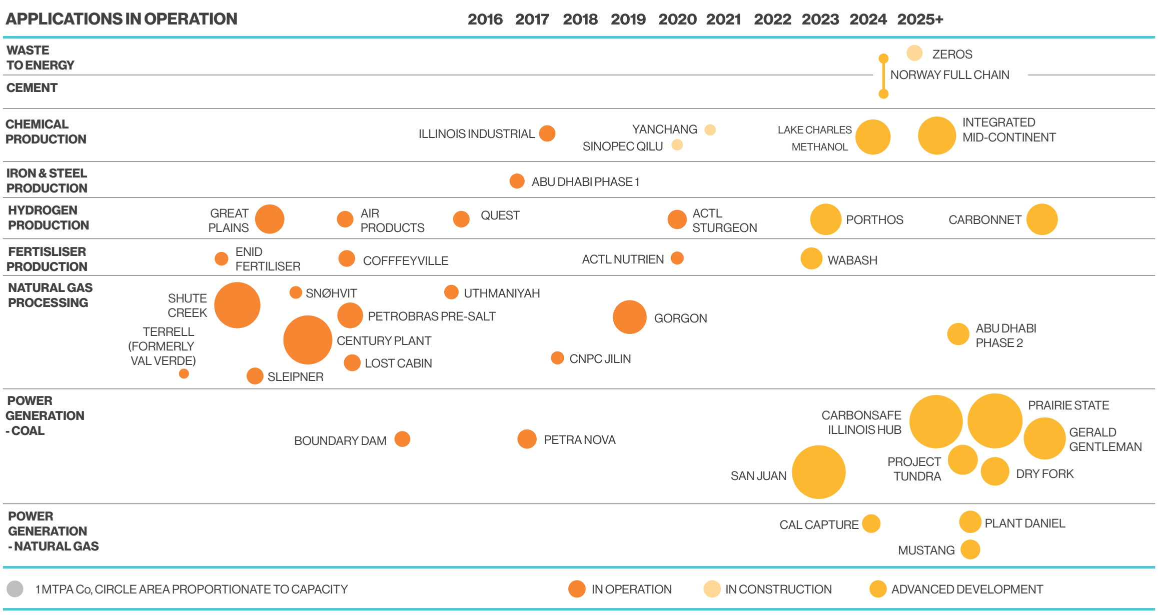
[4] Alcade, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M. V., Ogaya, X., Haszeldine, R. S., 2018, Estimating geological CO_2 storage security to deliver on climate mitigation, Nature Communications, Volume 9, Article number: 2201.

[5] Global CCS Institute 2019; Global Status of CCS 2019.

Current Carbon Capture and Storage Facilities

As of August 2020, 21 commercial CCS facilities with a total capacity of 40Mtpa CO_2 are operating, three more are in construction, 17 are in advanced development and approximately another 20 are in early development.[6] Each of these facilities is or will permanently store hundreds of thousands of tonnes of CO_2 per year, and several store more than one million tonnes of CO_2 each year. Five of the 21 operating facilities use dedicated geological storage (I.E. no EOR) including Gorgon, the world's largest with a capacity to store 4Mtpa of CO_2. Nineteen of the 21 operating facilities are capturing from industrial sources with relatively high concentrations of CO_2. Only two are on power generation; both are retrofits to coal fired power stations.

The strong bias towards non-power applications is a function of business case, not technology. All else being equal, the cost of capture increases as the concentration of CO_2 in the gas stream reduces. Consequently, capturing CO_2 from a power station which produces flue gas with only around 10% CO_2, is commercially more challenging than capturing CO_2 from a natural gas processing plant, which produces an almost pure stream of CO_2.



Source: Global CCS Institute

Figure 2. Commercial CCS Facilities by Industry, Commencement of Operation, & CO_2 Storage Option[6]

Similarly, the strong bias towards EOR rather than dedicated storage is also driven by commercial considerations. EOR creates a value driver for CO_2 storage through revenue from oil production that supports the business case for investment.

[6] Operation of Petra Nova has been temporarily suspended due to low oil price.

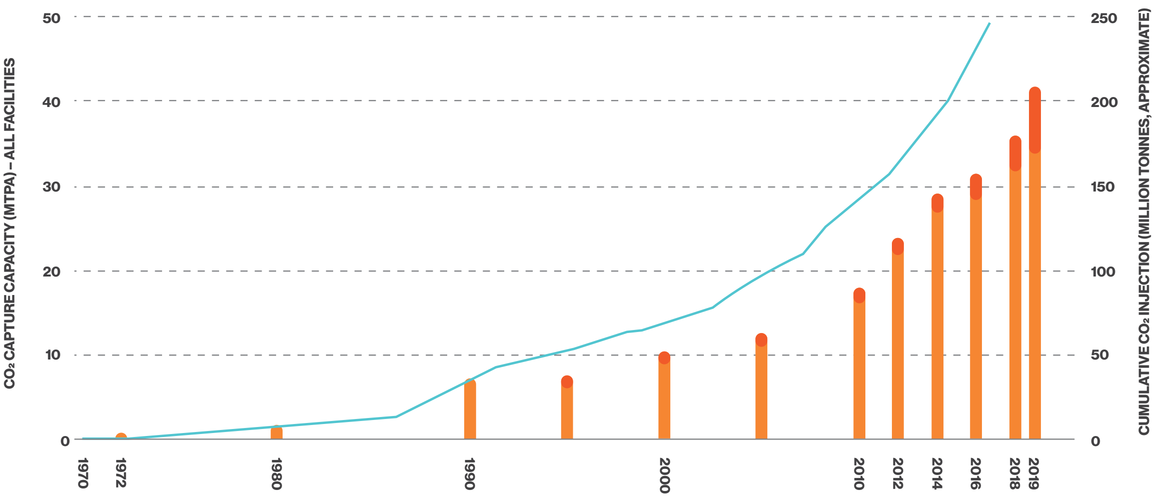


Figure 3. Installed Capacity and Cumulative CO_2 Injected

Bioenergy with CCS and Direct Air Capture with Storage (BECCS & DACS)

Analysis by the Intergovernmental Panel on Climate Change and others has concluded that Carbon Dioxide Removal (CDR) will be required to meet ambitious climate targets by reducing the stock of CO_2 in the atmosphere. This is in addition to urgent action to mitigate CO_2 emissions at their source. BECCS is a class of CDR, which uses biomass as a primary energy source with the capture and storage of CO_2 produced during production and/or utilization. BECCS transfers carbon from the atmosphere taken up by biomass during growth to permanent geological storage. There are currently five commercial BECCS plants operating, although these may not have been configured to achieve negative emissions on a life cycle basis; all capture CO_2 from fermentation-based biofuel production. The largest of these is the Illinois Industrial CCS Facility with a capacity of 1Mtpa of CO_2 from bioethanol production from corn. The captured CO_2 from this facility is stored in a dedicated geological storage resource.

BECCS also includes the combustion of biomass in thermal power plants to generate electricity, with CO_2 capture and geological storage. Biomass may be co-fired with fossil fuels or may completely replace fossil fuels in the boiler. Currently, biomass supplies about 52GW of power generation.[7] The Drax power station in the United Kingdom has converted three 660MW units from coal fired to 100% biomass fired. Drax uses sustainably sourced wood pellets produced

[7] Carbon Sequestration Leadership Forum 2018, Technical Summary of Bioenergy Carbon Capture and Storage (BECCS), Report prepared for the Carbon Sequestration Leadership Forum (CSLF) Technical Group

from wood processing wastes and in 2019, commenced operating a pilot plant to capture up to one tonne of CO_2 per day. When access to CO_2 transport and geological storage infrastructure becomes available in the UK, Drax will have the potential scale up its capture facilities to remove several million tonnes of CO_2 from the atmosphere every year.,

Waste to Energy (WtE) with CCS is another form of BECCS. Municipal waste contains a mixture of biogenic (plant based) and fossil-based materials. There are currently almost 2.5GW of WtE facilities operating around the world. If the biogenic component of the waste incinerated in a WtE facility is sufficiently large, and the CO_2 emissions are captured and stored, the plant will have net negative emissions. The capture of CO_2 from WtE facilities has been successfully demonstrated at the Saga City WtE facility in Japan and the Twence WtE facility in the Netherlands. In 2019, Twence signed an agreement with Aker Solutions for the supply of a 100,000 tpa CO_2 capture plant by 2021. Further, a 400,000 tpa CO_2 capture system with geological storage is in development at the Klemetsrud WtE facility in Oslo, Norway. This facility will have net negative emissions when operational.

Direct Air Capture technologies that remove CO_2 from the atmosphere are currently being developed and commercialized by several companies. The most advanced are Climeworks, Global Thermostat and Carbon Engineering which have all developed modular technologies that are scaleable. Carbon Engineering is currently designing a DAC plant with a capacity of 1Mtpa CO_2 for permanent geological storage with construction scheduled to commence in 2021. Global Thermostat has demonstrated their technology in a pilot plant with a capacity of 4000 tonnes of CO_2 per year and has now partnered with ExxonMobil to scale up their technology. Climeworks has 14 small scale direct air capture plants (eg approx. 1000 tonnes CO_2 per year) operating across Europe, providing CO_2 to industry (eg, food and beverage industry and for use in greenhouses). These plants are reusing the CO_2 . Climeworks has partnered with the Carbfix project in Iceland to remove CO_2 from the air and permanently store it in basalt rock formations where the CO_2 is mineralized in only two years. A pilot plant with a capacity of 50 tonnes CO_2 per year commenced operation in 2017. A 3000 tonne per year plant is now in construction.[8]

One advantage of DAC over capture from industrial or power sources is that it is not necessary to co-locate them with CO_2 sources. The sites for DAC plants may be chosen proximate to high quality geological storage resources and where the cost of energy is low providing the opportunity to reduce the capital and operating costs for this class of technologies. Even so, the cost of capturing CO_2 from the atmosphere, currently in the range of US$500-US$1000 per tonne of

[8] Clean Energy Ministerial CCUS Initiative Webinar (2020): Direct Air Capture of CO_2: Helping to Achieve Net-Zero Emissions, 21 April 2020.

CO_2 , is significantly more than from industrial point sources. However, the cost is falling and will fall further due, if nothing else, to economies of scale that arise from plant capacities increasing from thousands of tonnes per year to millions of tonnes per year. That cost may be $300 per tonne of CO_2 or less within the next decade. Currently, abatement costs approach or exceed $1000 per tonne for some sectors, and for others, there are no technologies that can reduce emissions to zero. DAC with geological storage of CO_2 offers the promise of capping the cost of abatement at the cost of DACS, obviating the need to deploy more expensive abatement options, and delivering abatement solutions where none currently exist.

This opportunity is shown graphically in Figure 4, adapted from a report published by Goldman Sachs in December 2019. In this figure, the red line represents abatement from "conservation" which is equivalent to the Reduce, Reuse and Recycle dimensions of the "4 Rs". The blue line represents abatement through Removal (eg, afforestation and CCS) with the highest cost removal options at the right of the curve being DACS.

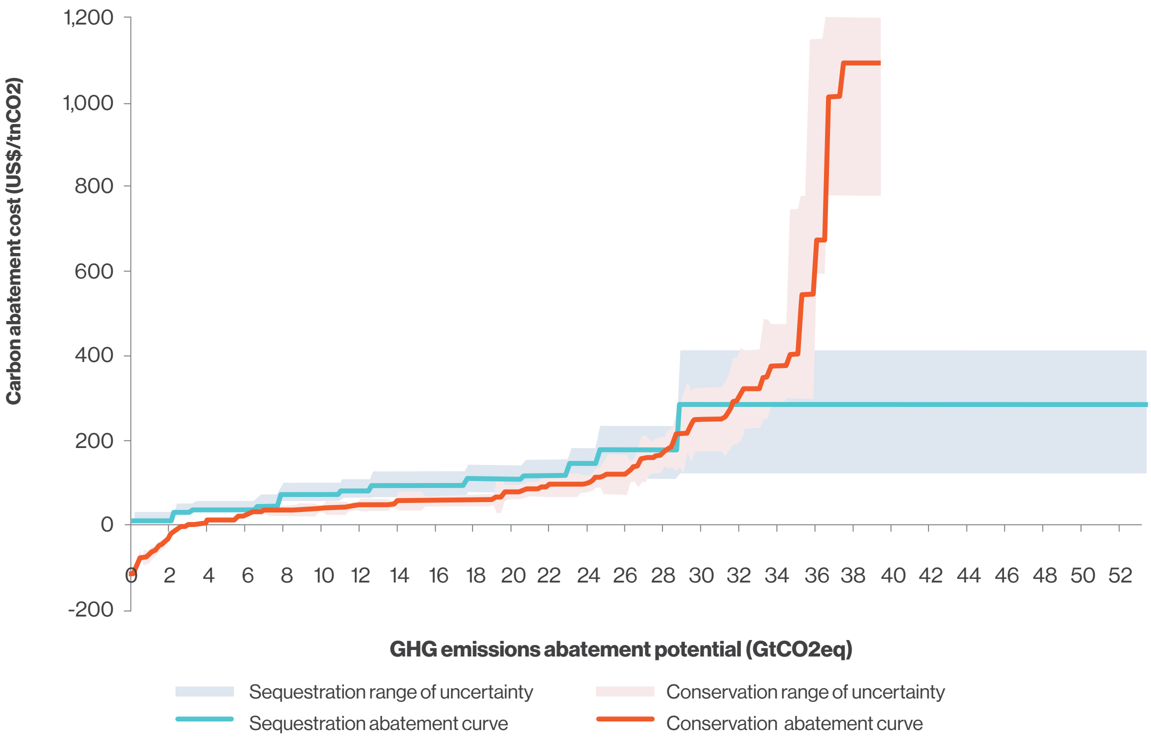


Figure 4. DACS can cap the cost of reaching Net Zero[9]

[9] Goldman Sachs, 2019. Carbonomics. "The Future of Energy in the Age of Climate Change."

Cost Drivers for CCS

There are three major components to a CCS value chain; capture of CO_2 at the source, compression and transport of the CO_2 to the storage site, and injection of the stored CO_2. Each has unique cost drivers.

All else being equal, carbon dioxide capture costs are inversely related to the concentration and pressure of CO_2 in the gas stream. Also, the size of the plant (and therefore the capital cost) designed for gas streams with low CO_2 concentrations will be larger than for high concentration gas streams simply because of the much larger total volume of gas required to be processed per tonne of CO_2 separated.

Before injection, CO_2 must be compressed to a supercritical state. This requires compression to pressures of at least 75 times atmospheric pressure.[10] Compression is capital and energy intensive and contributes a significant proportion of the total capital and operational cost of capturing CO_2 and presenting it ready for geological storage. The unit cost of compression reduces significantly with increasing scale. For example, compression costs for a 100ktpa facility may approach $25 per tonne compared to $13 per tonne for a 5Mtpa facility.[11] Processes that present CO_2 at higher pressures such as the NetPower plant based on the Allam cycle,[12] require less compression delivering cost reductions.

CO_2 is currently transported for geological storage or as a commodity product by pipeline, ship, road and rail. Transport of large volumes (millions of tonnes per year) via pipelines and smaller volumes (tens of thousands of tonnes per year) by ship, road and rail has been routinely undertaken for more than 30 years. Similar to compression, CO_2 transport costs reduce significantly with increasing scale. The volume of CO_2 associated with commercial CCS facilities requires transport by pipelines and/or ships. The preferred option is a function of volume and distance, with shipping generally being the lower cost option for distances of over 1000km.

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[10] 150 bar is typical for pipeline transport of CO_2.

[11] GCCSI analysis. Assumes US Gulf Coast costs.

[12] See section XX on Allam Cycle.

The quality of the geological storage resource is also a significant cost driver. Geological storage facilities are always operated to maintain reservoir pressures below their fracture pressure with a margin of safety. Poor quality geological storage structures with a low permeability and porosity will require more injection wells and/or longer injection intervals to spread the injection of CO_2 over a larger volume to ensure that reservoir pressures are kept acceptably low. In some reservoirs, water production wells may be required to manage reservoir pressures. Additional wells for injection and reservoir pressure management required in lower quality storage reservoirs will add cost to the storage operation compared to good quality storage reservoirs requiring fewer injection wells and no water production.

In addition to the factors described above, other significant cost drivers include the cost of energy, consumables, equipment and labor at the location where the facility has been constructed and the cost of capital. A high-risk lending rate alone can add tens of millions of dollars to the annual cost of servicing debt compared to a low-risk lending rate.[13] Notwithstanding site-specific factors and the cost of capital, Figure 5. provides indicative ranges for the cost of the major components of a CCS facility assuming construction on the Gulf of Mexico in the USA.

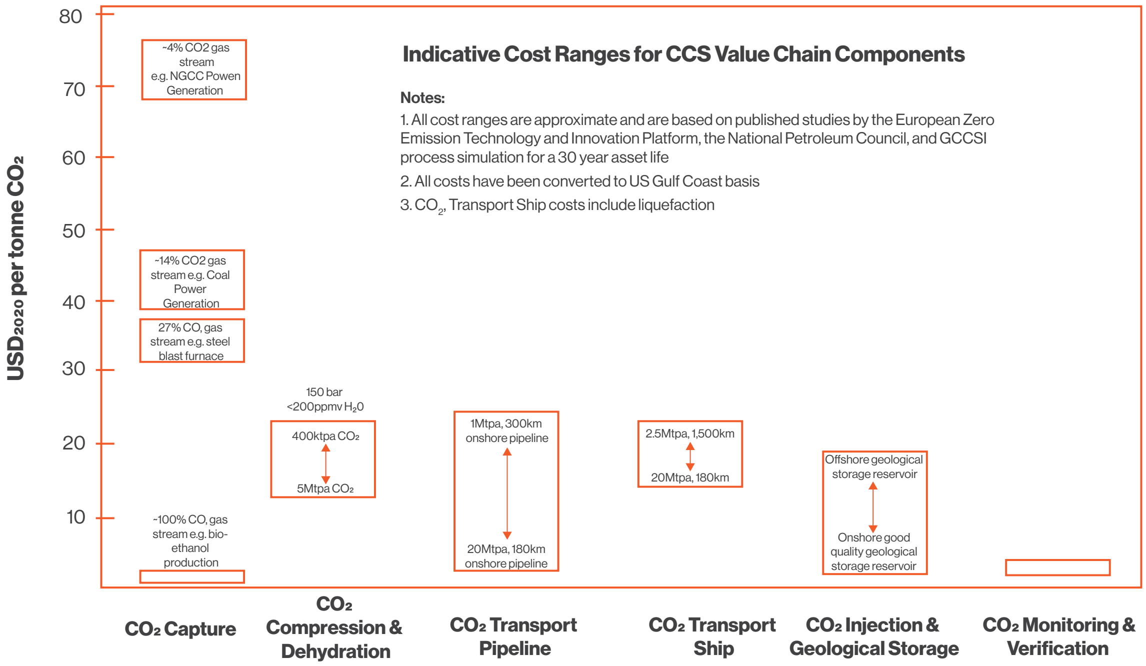

Figure 5. Indicative Cost Ranges for CCS Value Chain Components – US Gulf Coast[14]

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[13] GCCSI 2019; Policy Priorities to Incentivize Large Scale Deployment of CCS.

[14] Based on GCCSI process simulation and analysis of: ZEP 2019, The cost of subsurface storage of CO_2, ZEP Memorandum, December 2019. IEAGHG ZEP 2011, The Costs of CO_2 Storage, Post-demonstration CCS in the EU. National Petroleum Council 2019, Meeting the Dual Challenge, A Roadmap to at-scale deployment of carbon capture use and storage. National Petroleum Council 2019, Topic paper #1, Supply and Demand Analysis for Capture andf Storage of Anthropogenic Carbon Dioxide in the Central US.

Figure 5 should be used with caution. Costs are always project specific. There are significant variations in the cost of capital, of capital equipment, of labor, of energy and other consumables between locations. Project characteristics also determine project costs in any location. For example, the Northern Lights project, which plans to transport CO_2 by ship from various ports to a storage site under the seabed of the North Sea, is targeting storage costs of €35-50/tCO_2 which is considerably higher than the shipping costs shown in Figure 5.[15]

Capture Costs are Reducing

The cost of CO_2 capture from low concentration sources such as coal fired power generation has reduced by approximately 50% over the past decade or so, driven by the familiar processes that accompany the development and deployment of any industrial technology. Studies of the cost of capture and compression of CO_2 from power stations completed ten years ago averaged around USD_{2020}5/tCO_2. Comparable studies completed in 2018/2019 estimated capture and compression costs of approximately USD_{2020}50/tCO_2.

Two coal fired power plant CCS retrofits have been constructed and have commenced operation since 2014.[16] These two facilities used different proprietary capture technologies and adopted different retrofit strategies with respect to the integration of the capture plant with the power plant so they are not directly comparable. However, the difference in actual capture and compression costs observed in these two facilities is consistent with the trend observed in studies. Capture costs for Boundary Dam in Canada, which commenced operation in 2014, are approximately USD_{2020}105/tCO_2 compared to Petra Nova in the USA, which commenced operation in 2017 with capture and compression costs of approximately USD_{2020}70/tCO_2. In both cases, the developers of these facilities advised that if they built the facility again, they could reduce the capital cost by at least 20% by applying what they had learned from their first project.

[15] Aasen E.I., and P. Sandberg. 2020. Northern Lights. A European CO_2 transport and storage network. Presentation by Equinor to the Zero Emissions Platform (ZEP) Conference, European Parliament. 28 January 2020; Brussels.

[16] Operation of Petra Nova has been temporarily suspended due to low oil price

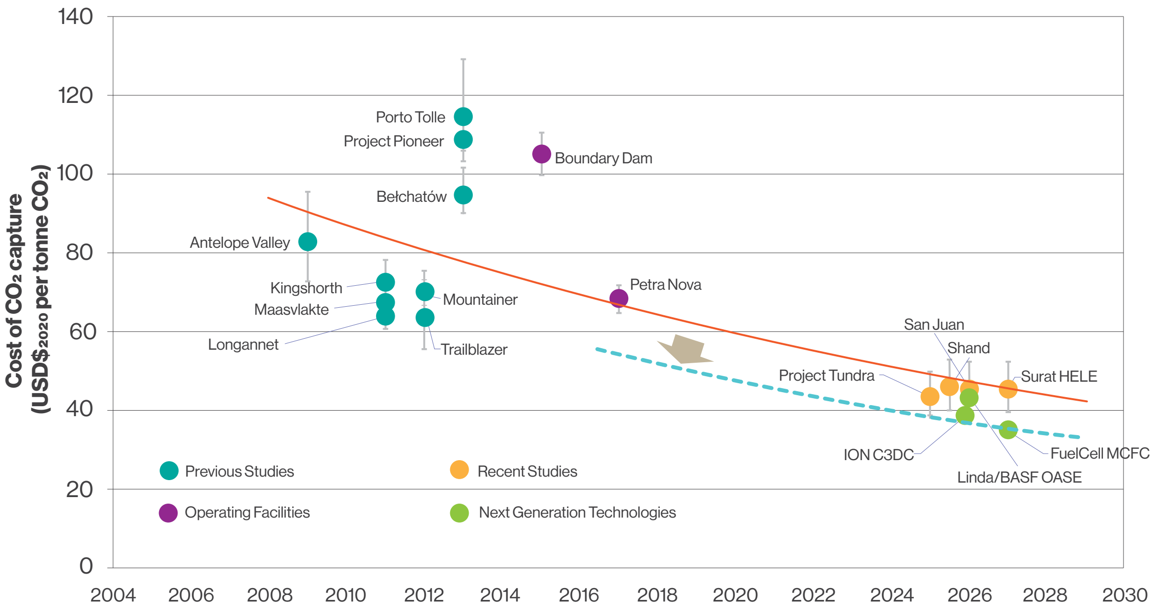

Figure 6. Evolution of CO_2 Capture Costs (ION C3DC, Linde/BASF and Fuel Cell MCFC are claimed cost by technology developers)

03
Outlook

Outlook

Fundamental Drivers of CCS are Strengthening

Whilst the business case for investment in CCS is not yet sufficient to drive deployment at the rate necessary to achieve climate stabilization, it is growing. Evidence of this trend is clearly visible in Figure 7. which shows the total capacity of the CCS project pipeline from 2010 to May 2020. Total capacity in the pipeline decreased year on year between 2010 and 2017. This was probably due to a combination of factors including public and private sector focus on short term recovery following the Global Financial Crisis. However, for the past three years, the pipeline has grown strongly. Today there are more than four times as many commercial CCS facilities operating than there were in 2010 and the total capacity of facilities at various stages of study has tripled since 2017.

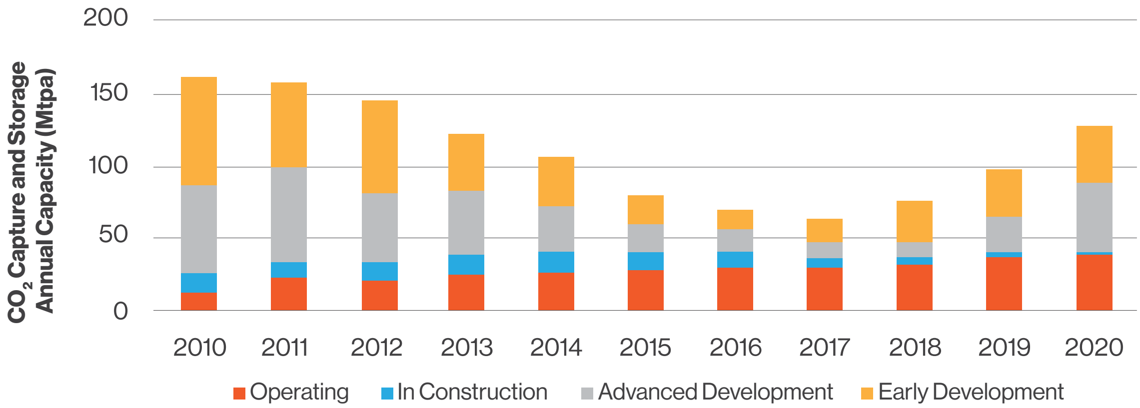

Figure 7. Pipeline of Large-Scale CCS Facilities from 2010 to May 2020[17]

[17] GCCSI Analysis

Growth since 2017 has been driven by a number of factors including recognition of the increasing urgency of achieving net-zero greenhouse gas emissions. That recognition was given effect in the 2015 Paris Agreement that established a clear ambition to limit global warming to less than 2 degrees Celsius. Since 2015, ambition for emissions reductions has strengthened with limiting warming to 1.5 degrees Celsius becoming a more commonly stated target. This has refocused governments, the private sector and civil society on emissions reduction. Governments have responded through enacting stronger climate policy and shareholders have applied greater pressure on companies to reduce their scope one, two and three emissions. For example, around 50 countries, states/provinces or cities and hundreds of companies have now committed to achieving net-zero emissions by midcentury. Further, there is a slow movement of capital away from high emission asset classes to lower emission asset classes as demonstrated by the rise of Environment Social Governance (ESG) investment funds and green bonds and increasing limitations on the availability of debt financing for coal-related investments. The need to address hard to abate sectors such as steel, fertilizer, cement and transport has become more prominent and is no longer delayed to future analysis. These global macro-trends have motivated a more thorough analysis of how to achieve net-zero emissions at the lowest possible risk and cost. A conclusion which may be drawn from these analyses is that the cost and risk of emissions reduction is minimized when the broadest portfolio of technologies, including CCS, is available. Further, it is clear that achieving net zero without CCS is practically impossible.

Next Generation CO_2 Capture Technologies

As recognition of the need for CCS grows, research and entrepreneurial activity is developing the next generation of capture technologies that will build upon the significant cost reductions already observed over the past decade. Brief descriptions of a selection of some of the most advanced new technologies follow.

Water-Lean solvent capture technology – Ion Clean Energy

Ion's water lean-solvent capture technology is similar to commercially available aqueous amine-based systems. However, instead of using water, Ion uses an organic solvent. This organic solvent significantly reduces the regeneration energy penalty while having higher CO_2 loading capacities. Ion has completed pilot-scale testing with multiple flue gas types at up to 12-MWe scale. Initial testing results indicate a preliminary capture cost estimate of US$35 – 44 per tonne of CO_2 from a power station. In 2018, Ion was awarded US$2.7 million by the US DOE for a techno-economic assessment of a commercial-scale (300 MWe) CO_2 capture facility at the Nebraska Public Power District's Gerald Gentleman Station Unit 2 in Sutherland, Nebraska (Global CCS Institute 2019).

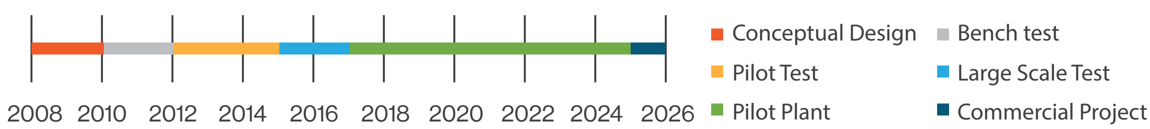

Figure 8. Ion Clean Energy Commercial Timeline

DMX™ Process - IFP Energies Nouvelles (IFPEN)/Axens

The DMX™ process uses phase change solvents developed by the French Institute of Petroleum Energies Nouvelles (IFPEN). It will be marketed by Axens. Two non-miscible phases are formed upon CO_2 capture. The heavy phase with higher CO_2 loading is sent to the desorber for regeneration. This configuration reduces regeneration energy and enables the use of lower cost carbon steel, as well as operation under higher pressure/temperature conditions. In May 2019, ArcelorMittal, Axens, IFPEN, and Total announced the DMX™ Demonstration in Dunkirk (3D) project at a steel mill operated by ArcelorMittal in Dunkirk, France. Construction of the pilot project with a capture capacity of approximately 10 tonnes per day CO_2 will commence in 2020. Operation is scheduled for 2021. CO_2 capture costs of less than 30 Euro per tonne from the steel mill are expected. Operation of the first commercial DMX™ capture plant at the ArcelorMittal site with a capture capacity of over 1Mtpa could begin as early as 2025.

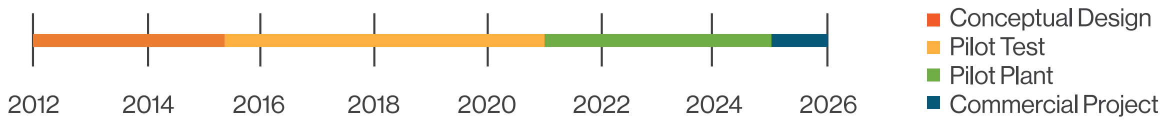

Figure 9. DMX Commercial Timeline

VeloxoTherm™ Temperature Swing Adsorption - Svante

The Svante VeloxoTherm™ process uses proprietary solid sorbents to adsorb CO_2 from a flue gas stream. The adsorbents are arranged in a circular structure which is rotated (approximately 1 revolution per minute) to simultaneously expose different sectors of the structure to each step in the process. In step one, the adsorbent is exposed to the flue gas where CO_2 binds to the surface of the absorbent. In step two, steam passes through the loaded absorbent structure, heating it and releasing the CO_2. The CO_2 is then easily separated from the steam (by condensing the steam to water) and is ready for compression. In the final step, the adsorbent is rotated into a cold air stream to cool it and prepare it for loading with CO_2. Capture costs are projected to be approximately US$33 per tonne of CO_2 for a plant with a capacity of 3 million tonnes per annum.

The VelexoTherm process was successfully demonstrated at a 0.5 tonne per day pilot during 2017. A 30 tonne per day capture plant is being commissioned by Husky Energy at a steam generator it operates in Saskatchewan, Canada.

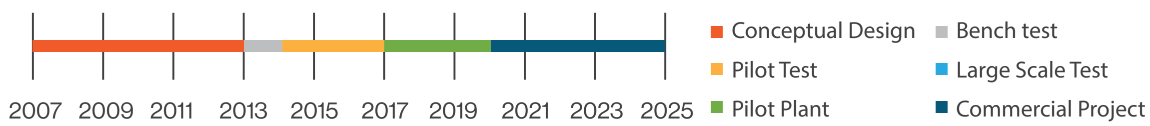

Figure 10. VeloxoTherm Commercial Timeline

Polaris™ Membrane – Membrane Technology and Research

Membrane Technology and Research, Inc. (MTR) has developed its proprietary PolarisTM membrane which uses hydrophilic polymer composites with isoporous support. These membranes have approximately ten times higher CO_2 permeance than commercial cellulose acetate membranes.[18] In 2016, MTR completed a 1,400-hour field test of its membrane in a 20 tonne per day pilot plant at the National Carbon Capture Center in Alabama, USA. A large pilot plant capturing 200 tonnes per day of CO_2 at the Wyoming Integrated Test Center associated with Basin Electric Power Cooperative's Dry Fork Station is currently in development.

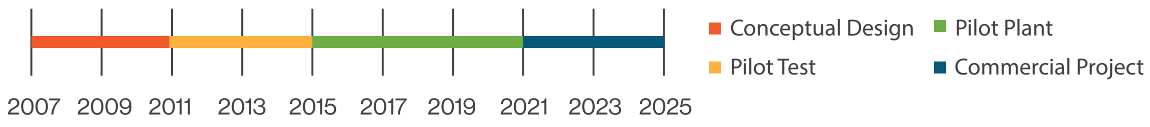

Figure 11. MTR Polaris Commercial Timeline

Molten carbonate fuel cell with electrochemical membrane - FuelCell Energy

Fuel cells convert the chemical energy of gaseous fuels to electrical energy and heat. Molten carbonate fuel cells (MCFCs) are one type of fuel cell currently being developed. They are high-temperature (550-650°C) fuel cells using a molten alkali metal (Li/Na/K) carbonate salt mixture as electrolyte. Carbon dioxide in flue gas reacts with oxygen to form carbonate ions at the cathode of the cell. The carbonate ions then travel through the electrolyte to the anode where they combine with hydrogen to produce water and CO_2 and the fuel cell generates electricity. The CO_2 is then separated from the water ready for compression.

FuelCell Energy, in collaboration with Southern Company and AECOM Technical Services, is developing MCFCs under the trade name of Direct FuelCell® .[19] In 2015, FuelCell Energy was supported by the US DOE to start a pilot 2.8 MWe MCFC power plant which captures CO_2 from the exhaust of a coal-fired power plant. In October 2016, FuelCell Energy partnered with ExxonMobil to develop a pilot project to capture CO_2 from natural gas-fired power turbines. The James M. Barry Electric Generating Station in Alabama, a 2.7 gigawatt (GW) mixed-use coal and gas-fired power plant was selected as the host site. This pilot project utilises FuelCell Energy's

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[18] Membrane Technology and Research 2009, Membrane Process to Sequester CO_2 from Power Plant Flue Gas, accessed from https://www.osti.gov/servlets/purl/1015458-lNdTMC/

[19] NETL 2018a, Compendium of Carbon Capture Technology 2018, accessed from https://www.netl.doe.gov/sites/default/files/netl-file/Carbon-Capture-Technology-Compendium-2018.pdf

commercial SureSource3000® carbonate fuel cell power system to concentrate and capture 54 tonnes per day of CO_2 emissions from a slipstream of the exhaust flue gases at Plant Barry from a natural gas-fired generation unit under an agreement with ExxonMobil, and a slipstream of the exhaust flue gases from a coal-fired generation unit under an agreement with the US DOE.[20] Pilot test results indicate a preliminary cost of US$33.7 per tonne of CO_2 captured in the FuelCell Energy MCFC system.

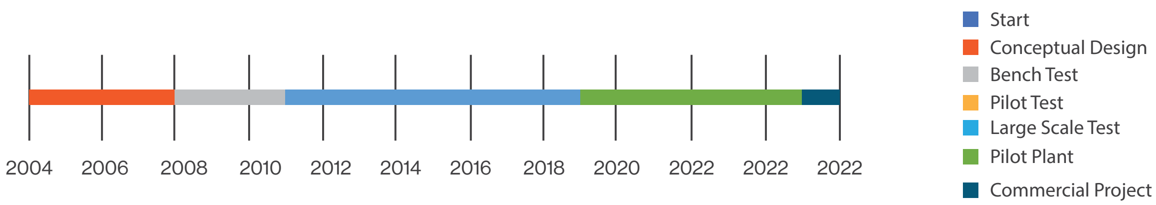


Figure 12. FuelCell Energy Commercial Timeline

Direct air capture – Carbon Engineering

Direct Air Capture (DAC) technology aims to capture CO_2 directly from the atmosphere. Current innovative DAC technologies use either basic solvents or solid sorbents as the capture media. Key technology suppliers include Carbon Engineering, Climeworks, and Global Thermostat.

The Carbon Engineering DAC system uses an extremely large, dispersed wet-scrubbing air contactor integrated with two chemical looping processes using potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$) to capture CO_2 from the atmosphere. Carbon Engineering has advanced its DAC technology through its concept study in 2009, the first front end engineering design of an air-liquid contactor in 2012, and the construction of the first pilot capture plant in Squamish, British Columbia, Canada for an ongoing capture test of one tonne per day of CO_2 in 2015. Carbon Engineering received US DOE funding of US$1.5 million in 2016 to advance the technology readiness of the DAC system, and to evaluate the techno-economic feasibility for a coal flue gas application.

In May 2019 Oxy Low Carbon Ventures LLC, a subsidiary of Occidental, and Carbon Engineering announced a joint project with a CO_2 capture capacity of 500,000 tonnes per annum.

[20] US National Energy Technology Laboratory 2018, 'Pilot Test of Novel Electrochemical Membrane System for Carbon Dioxide Capture and Power Generation,' accessed from https://www.netl.doe.gov/projectinformation

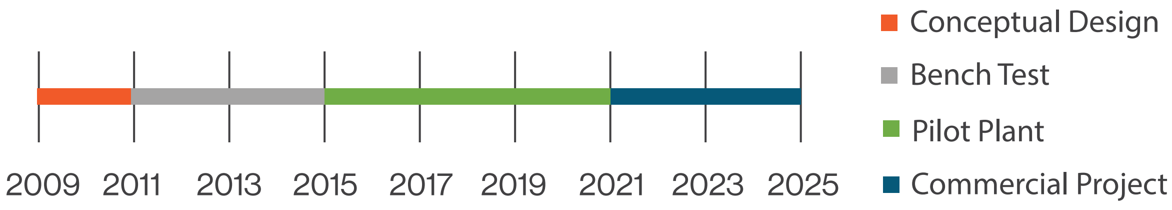


Figure 13. Carbon Engineering Commercial Timeline

Allam Cycle - NET Power / 8 Rivers Capital, LLC

The Allam Cycle is an innovative natural gas (or syngas) fired power generation technology. It involves oxy-fuel combustion and the use of the produced CO_2 as the working fluid which enables inherent CO_2 capture, compression, and dehydration as well as the elimination of NOx / SOx. The technology produces pipeline-ready CO_2 without the use of add-on carbon capture equipment. The technology was invented by Rodney Allam and funded by 8 Rivers Capital LLC, CB&I, and Exelon. NET Power LLC (NET Power) is currently commercialising the Allam Cycle in the natural gas industry while 8 Rivers is leading an industrial consortium in North Dakota and Minnesota to apply the Allam Cycle to syngas from coal/biomass/petroleum coke gasification.[21,22] All components of an Allam Cycle plant are commercially available except for the turbine and combustor. Toshiba developed, manufactured and supplied a hybrid turbine and combustor for use in the gas- fired pilot project.

8 Rivers Capital also plans to use the Allam Cycle and 8 Rivers hydrogen technology for coproduction of power and H_2 using natural gas feedstock. 8 Rivers H_2 technology is in early development and is featured in the New Zealand Pouakai H_2 roadmap.

The first Allam Cycle combustor using supercritical CO_2 as a working fluid was tested at 5 MWth scale in 2013. In March 2018, Net Power announced that it has successfully fired its 50 MWth first-of-a-kind natural gas-fired Allam Cycle power plant located near Houston, Texas. The design of a commercial-scale 303MW Allam Cycle natural gas plant is currently underway. A pre-FEED study for an Allam Cycle power production facility for potential deployment at multiple locations in the United Kingdom was announced by McDermott in June 2020.[23]

[21] NETL 2018a, Compendium of Carbon Capture Technology 2018, accessed from https://www.netl. doe.gov/sites/default/files/netl-file/Carbon-Capture-Technology-Compendium-2018.pdf

[22] Lu, X, Martin, S, McGroddy, M, Swanson, M, Stanislowski, J & Laumb, JD 2017, 'Testing of a Novel Post Combustion Acid Removal Process for the Direct- Fired, Oxy-Combustion Allam Cycle Power Generation System', no. 50961, p. V009T38A032, accessed from http://dx.doi.org/10.1115/GT2017-65217

[23] http://www.mcdermott-investors.com/news/press-release-details/2020/McDermott-Awarded-Pre-FEED-for-NET-Power-UK-Project/default.aspx

The natural gas Allam Cycle is projected to produce electricity at a levelised cost of approximately US$65/MWh in the United States with greater than 97 per cent CO_2 capture. When sales of co-produced industrial gasses, i.e. CO_2 (US$35 per tonne for EOR under 45Q in the US), N2, Ar, etc are factored into the cost calculations, the natural gas Allam Cycle is capable of producing electricity with 97% CO_2 capture at a levelized cost of US$19/MWh. For the coal-fuelled Allam Cycle with >97 per cent carbon capture, the preliminary estimate of the cost of electricity is US$62/MWh.[24]

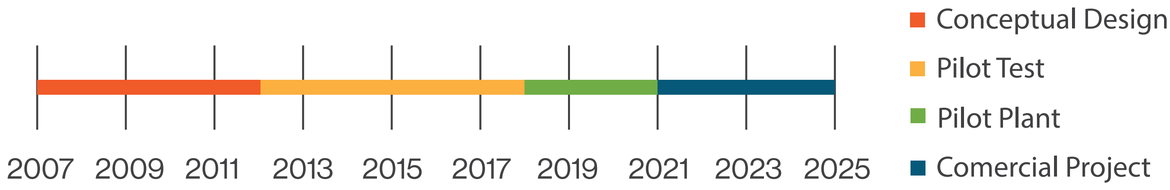


Figure 14. NetPower AllamCycle Commercial Timeline

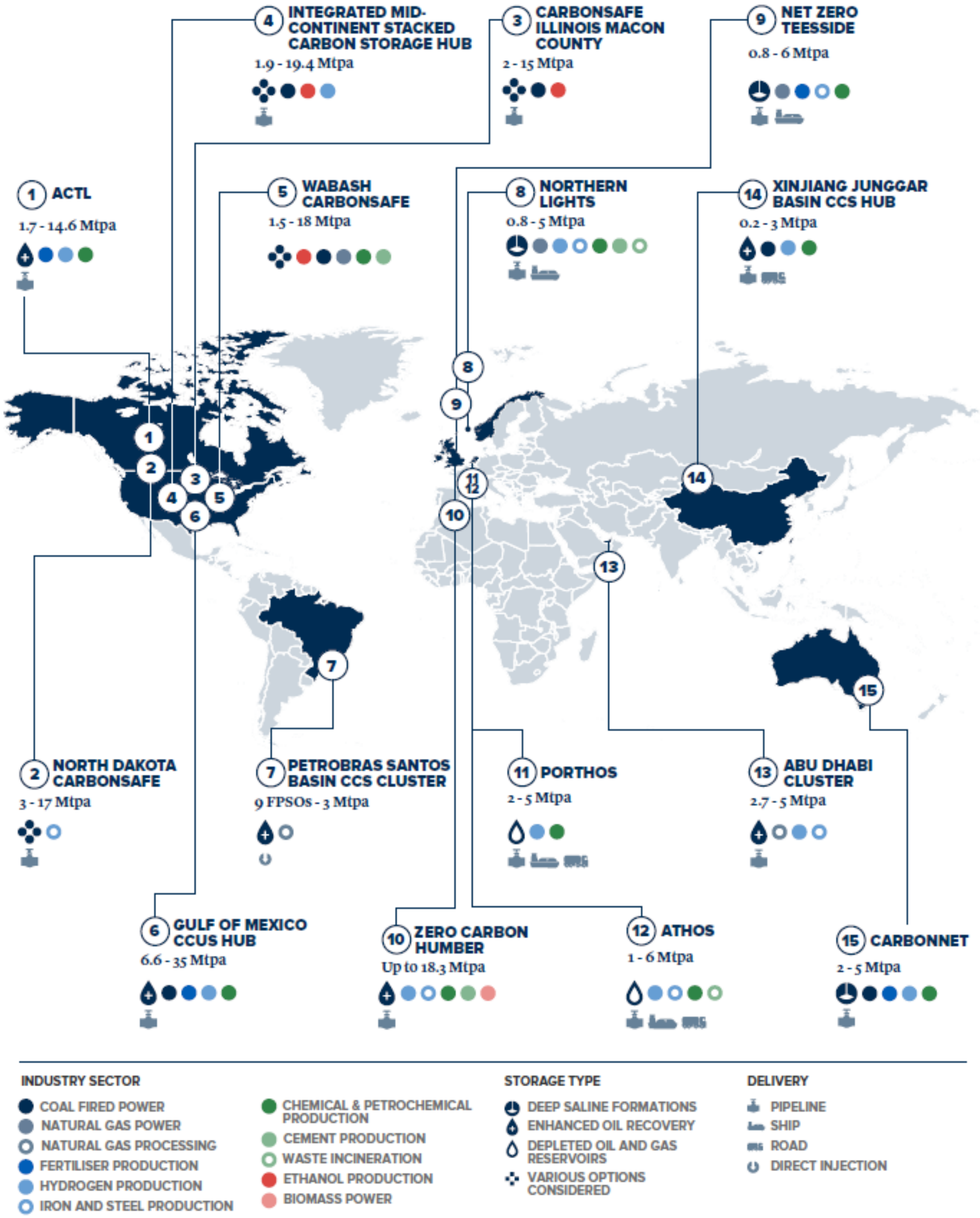
Industrial CCS Hubs and Clusters

Industrial CCS hubs and clusters are emerging as the next wave of CCS investment. These hubs feature multiple industrial sources of CO_2 accessing common CO_2 transport and injection infrastructure. CCS hubs significantly reduce the unit cost of CO_2 transport and storage through economies of scale, and also offer commercial and technical synergies that reduce the risk of investment and further reduce cost. For example, an industrial hub provides the opportunity to combine multiple small carbon dioxide streams from different industrial processes into one large stream for compression in a single facility reducing the unit cost of compression through economies of scale. CCS hubs also mitigate cross-chain or counterparty risk and the risk of low utilization of CO_2 transport and injection infrastructure by creating an ecosystem of businesses that require CO_2 management and storage services. The co-location of industries also benefits from the concentration of supply chains, and the availability of factors of production and infrastructure to transport products to market.

In many cases, industrial hubs (without CCS) already exist due to the availability of factors of production, access to infrastructure etc. Transforming these emissions intense industrial hubs into low emissions hubs by applying CCS will provide a *just transition* for the communities that rely upon them for employment. It will also create new investment and high-value jobs and the potential of attracting new industries that require a CO_2 management solution. The social and economic benefits of CCS hubs are a strong driver of growing interest in them.

[24] NET Power 2019, NET Power Presentation, accessed from https://energyatkenanflagler.unc.edu/wp-content/uploads/2019/04/NET-Power-UNC-DamianBeauchamp-March-29-2019.pdf

Most of the CCS facilities that entered the development pipeline over the past couple of years have been associated with hubs. Figure 15 identifies CCS hubs and clusters that were either operating



or progressing through studies in 2019.

Figure 15. CCS Hubs and Clusters Operating or in Development

04

Carbon management potential

Carbon management potential

CCS encompasses a versatile suite of technologies that can be applied to almost any source of carbon dioxide. It is this versatility that underpins its enormous carbon management potential.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report published in 2014 found that excluding CCS from the portfolio of climate mitigation technologies resulted in a more than doubling of the cost of limiting the concentration of CO_2 in the atmosphere to 450ppm (equivalent to global warming of approximately two degrees Celsius). The International Energy Agency's Sustainable Development Scenario, which is consistent with stabilizing global warming at less than two degrees Celsius requires 2.8Gt of CO_2 to be stored each year by 2050. The International Panel on Climate Change's Special Report on Global Warming of 1.5 Degrees Celsius published in 2018 reviewed 90 scenarios, almost all of which required CCS to limit global warming to 1.5 degrees Celsius. The average mass of CO_2 permanently stored in the year 2050 across all scenarios reviewed by the IPCC report is 10Gt. The IPCC constructed four illustrative pathways to represent the range of 1.5 degree scenarios in the models it reviewed. Three of the four illustrative pathways require CCS with cumulative CO_2 storage to the year 2100 of between 348Gt and 1,218Gt.

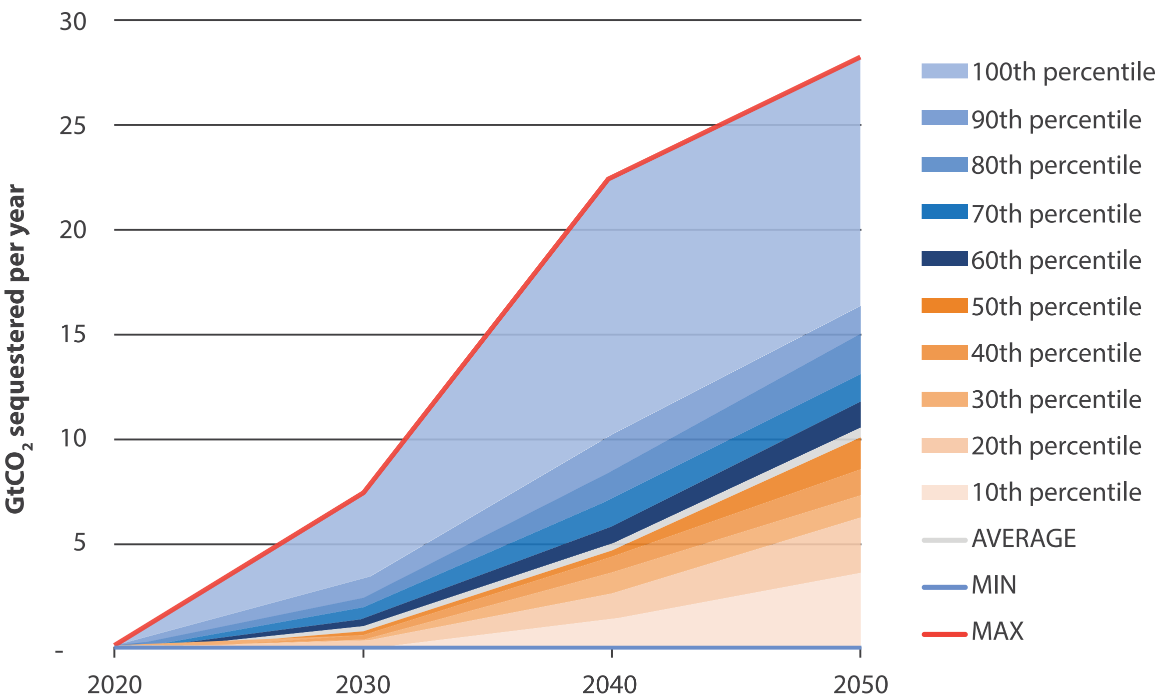


Figure 16. Annual CO_2 sequestration in the 90 1.5°C consistent scenarios used by IPCC[25,26]

As the IPCC report demonstrated, it is possible to construct a scenario where global warming is limited to 1.5 degrees Celsius without CCS, however this requires final energy demand to reduce by one third compared to 2010 by 2050. [27] Against a backdrop of a growing global population and rising affluence, particularly amongst the least developed nations, material reductions in final energy demand appear to be improbable. Similarly, at the other end of the spectrum, the deployment of CCS at the rate and scale necessary to store over 1200Gt of CO_2 by 2100 carries significant risk. In reality, the pathway with the lowest risk probably lies somewhere in the middle. In any case, it is clear that CCS has a carbon management potential this century of hundreds to thousands of billions of tonnes of carbon dioxide.

Whilst the analyses mentioned above are models and scenarios, not predictions of the future, the general conclusion to be drawn from them, and many others completed over the past twenty years, is that the lowest cost, lowest risk path to achieving net-zero emissions requires all available technologies including CCS. Each technology will deploy where it offers the best solution depending upon local conditions and resources. In many circumstances, CCS will not be the best option. In many other circumstances, CCS will be the best option and in some circumstances, CCS will be the only option.

CCS in Electricity Generation

Power generation is currently the largest source of greenhouse gas emissions, accounting for around a third of anthropogenic CO_2 emissions.[28] Moreover, the electrification of transport and heat is expected to significantly increase electricity demand in the coming decades. Constructing a near-zero emission power generation system is critical to reach net-zero emissions and meet long-term climate mitigation goals. This will require a mix of technologies including solar, wind, hydroelectric, nuclear, biomass and fossil fuel fired generation with CCS.

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[25] Global CCS Institute Analysis of IIASA 1.5C Scenario Explorer.

[26] R. Z. Daniel Huppmann, Elmar Kriegler, Volker Krey, Keywan Riahi, Joeri Rogelj, Katherine Calvin, Florian Humpenoeder, Alexander Popp, Steven K. Rose, John Weyant, Nico Bauer, Christoph Bertram, Valentina Bosetti, Jonathan Doelman, Laurent Drouet, Johannes Emme, "IAMC 1.5°C Scenario Explorer and Data hosted by IIASA," Integr. Assess. Model. Consort. Int. Inst. Appl. Syst. Anal., no. Release 2.0, 2019.

[27] IPCC, "Global Warming of 1.5 degrees C; Summary for Policy Makers", 2018.

[28] IEA, "World Energy Outlook 2019," 2019.

An electricity system capable of supporting modern industrialized economies requires dispatchable or firm power generation capacity. This is generation capacity that can be ramped up or down at any time in response to changes in demand. The power produced by intermittent energy sources such as solar photovoltaic or wind depends upon the availability of the natural primary energy resource (solar radiation or wind), independent of demand. This creates difficulties for electricity systems; grid operators must not only manage variability in demand for electricity, but also variability in supply. As the penetration of intermittent renewables in a grid increases, the variability in supply increases and the capacity of firm generation which may be ramped up or down to balance supply and demand decreases. This is generally manageable where firm generation capacity supplies the significant majority of electricity in a grid. However, at higher levels of intermittent renewable energy penetration, other measures are required. Those measures, which all add to the cost of delivered electricity, include a combination of the following:

- Energy storage
- Additional electricity transmission lines (to provide access to renewable capacity across a broader geographical area to reduce variability in supply caused by local weather conditions)
- Installation of smart electricity meters to enable demand side management where supply is otherwise not able to meet demand.

Energy storage is particularly challenging. The only large-scale energy storage that is feasible today is pumped hydro which can provide hundreds of GWh of energy storage. The deployment of pumped hydro storage is limited by access to terrain with the necessary relief and the availability of large volumes of water. Batteries can and do play a valuable role in managing short term intermittency (minutes to hours) of renewable generation, however it is not feasible for batteries to provide backup over a period of days or weeks, as would be required if a grid contained no dispatchable generation capacity. For example, consider the world's largest lithium ion battery installed in South Australia. It has the capacity to supply 100MW of electricity to the grid for 75 minutes.[29] Battery storage is limited by its relatively low energy density and high cost.

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[29] A. E. M. Operator, "Initial operation of the Hornsdale Power Reserve Battery Energy Storage System," 2018.

Further, a system with little or no dispatchable generation capacity would require installed renewable capacity of several times the average demand of the system due to their low capacity factor, and the need to produce excess power that can be stored when the resource is available. Solar photovoltaic generation capacity factors may exceed 30% in regions with an excellent solar resource or with solar tracking systems with typical values being around 20%.[30] Wind generation may achieve capacity factors of over 60% for offshore installations; however, 40% is typical for onshore installations.[31] These approximate figures are for regions with very high quality renewable resources. For example, solar PV capacity factors in Germany are around 15% or less.

In addition to ensuring that the quantity of electricity available at every moment equals demand, grid operators must also ensure that the frequency and voltage of supplied electricity constantly meets system requirements. For example, the frequency of power supply in Great Britain must always be between 49.5Hz and 50.5Hz. Power plants that utilise conventional generators (e.g. nuclear, hydro, fossil fuel or biomass) provide essential grid-stabilising services such as inertia, frequency and voltage control in addition to generating electricity. They are "synchronous generators" as they are all spinning at the same rate; 50 times per second for a 50Hz system, 60 times per second for a 60Hz system. They are also all "in phase" which means all the generators are at precisely the same physical position in their rotation at all times. This synchronisation creates the frequency of the power supply. The generators and the turbines that drive them are large heavy objects with a lot of angular momentum. That angular momentum creates inertia which is a resistance to change in the rate at which the generators spin. When electricity demand increases (or decreases) the inertia of the generators reduces the rate of change in the spin rate (and hence the rate of change of frequency and voltage) and provides sufficient time for other systems to adjust supply to bring it back into balance with demand. If there is insufficient inertia in an electricity grid, the system will not be able to bring supply into balance with a change in demand quickly enough to avoid a fall (or rise) of frequency and voltage beyond acceptable parameters, causing the system to trip-out. Synchronous generators also provide reactive power which is essential for grid stability.

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[30] Lawrence Berkeley National Lab, "Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States – 2019 Edition," no. September, p. 55, 2019.

[31] A. Z. Smith, "UK Offshore wind capacity factors," 2020. [Online]. Available: https://energynumbers.info/uk-offshore-wind-capacity-factors.

Intermittent renewable generators such as solar PV and wind are not synchronous, and thus cannot deliver essential grid stabilising services such as inertia, voltage and frequency control in the same way as synchronous generators. As the penetration of intermittent renewable energy technologies in an electricity grid increases replacing synchronous generators, inertia in the grid will decrease and at high levels of penetration, become insufficient to stabilise the grid without other measures being taken such as the installation of synchronous condensers, and additional reactive power compensating devices. The result is rapidly escalating grid-integration costs with increasing renewable penetration.

Any electricity system encompasses far more than just the generators, and the cost of delivered electricity is comprised of far more than just the cost of generation. To illustrate, electricity generation represented less than 40% of the total residential electricity price in Australia in 2019. Cost optimization must be based upon the total system cost, not just the cost of generation.

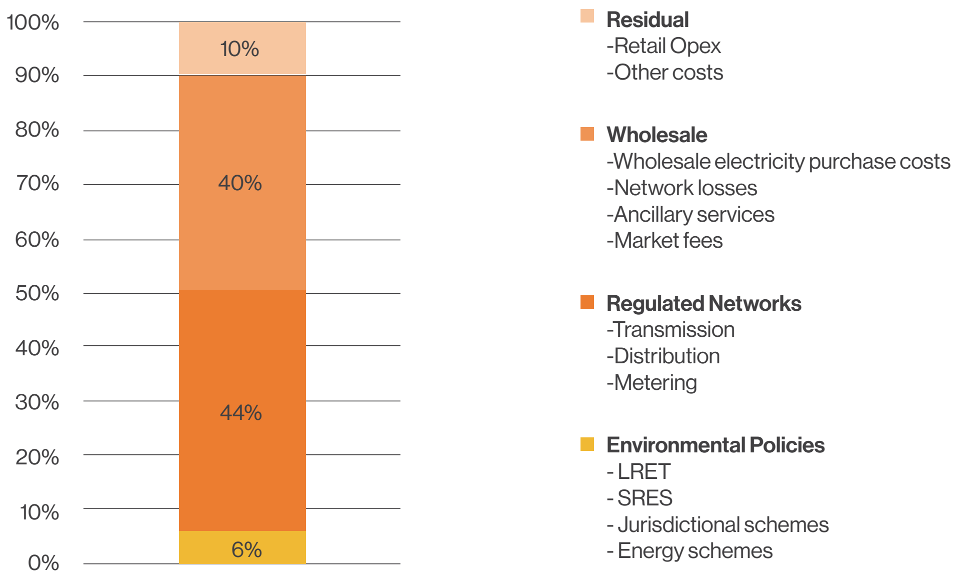

Figure 17. Breakdown of the national annual residential electricity price in 2019 in Australia. [32]

[32] Global CCS Institute analysis of Australian Energy Market Operator (AEMC), Residential Electricity Price Trends 2019.

The value of renewable generation is that it supplies near-zero emission energy to the grid with low generation costs in areas with high quality renewable resources. The value of near-zero dispatchable synchronous electricity generation such as nuclear, hydroelectric or fossil fuel/ biomass fired with CCS is that it provides near-zero emission power and does not incur any additional grid integration costs thereby reducing the total system cost of a near-zero emissions electricity system.

The optimum mix of near zero power generation technologies in a grid will change from place to place depending upon access to natural resources, the nature of the power grid, electricity demand profile and many other factors. Its is clear that all options are required including fossil fuel or biomass fired generation with CCS.

CCS is Required to Mitigate Emissions from New & Existing Fossil Power Generation

Scenarios used to chart possible pathways to achieving climate goals assume varying rates of fuel switching from higher emission primary energy sources towards lower emissions energy sources as well as changes in energy demand. For example, the utilization of coal is generally assumed to reduce rapidly. This is clearly evident from the four Illustrative Pathways developed by the IPCC to represent the range of pathways towards 1.5 degrees Celsius in its special report on Global Warming of 1.5 Degrees Celsius.

Table 1. Coal Utilisation Reductions assumed in IPCC Illustrative Pathways

IPCC Illustrative Pathway to 1.5 degrees C	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Reduction in primary energy from coal in 2030 compared to 2010	-78%	-61%	-75%	-59%
Reduction in primary energy from coal in 2050 compared to 2010	-97%	-77%	-73%	-97%

It is useful to compare actual outcomes and trends to those assumed in scenarios. Investment in fossil fuel power generation has been steadily falling over the past decade from approximately USD_{2018} 170 billion in 2010 to approximately USD_{2018} 120 billion in 2018.[33] Nonetheless, the global coal and gas fleets continue to grow, albeit at a declining rate. This trend is expected to continue. At some point retirements of plant will exceed new capacity additions and the global fossil fuel power fleet will begin to shrink. However, these facilities have economic lives of decades and a large global fleet of coal and gas fired power stations will remain in operation well past the middle of this century.

Consider coal for example; globally there are approximately 2000GW of operating coal fired capacity, and over 500GW of new capacity expected to come online by 2030, of which over 200GW of capacity is already under construction. Rather than falling by 60-80% by 2030 as assumed in the IPCC Illustrative Pathways, primary energy from coal appears set to increase by the end of this decade. Coal fired generation plant have an average operational life of 40-50 years so all of this new capacity is expected to remain in operation through to 2060 unless plants are closed prematurely. Considering only plants that are currently operating and under construction, and expected retirements, CO_2 emissions from the global coal fleet are expected to approach 10GtCO_2 in 2030 and exceed 7GtCO_2 in 2050.[34] To achieve a 1.5 degree Celsius climate target, around 90% of those emissions must be captured and stored in 2030, and effectively all emissions must be captured and stored in 2050.[32] Of course these emission projections are not inevitable. Policy and market conditions are likely to result in these plants operating at a lower average capacity factor than assumed and will result in some early retirements, particularly in developed economies. However, even if power production from the global coal fleet is only half what has been assumed in this simple illustrative analysis, approximately 85Gt of CO_2 must be captured and stored from coal fired power generation alone between 2030 and 2050 to be consistent with a 1.5 degree Celsius climate outcome.

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[33] IEA, World Energy Investment 2019.

[34] Cui et al, 2019, Quantifying operational lifetimes for coal power plants under the Paris Goals, Nature Communications 10:4759.

CCS in Industry

CCS is essential to achieve deep emission reductions in industry which produces about 8 billion tonnes of direct CO_2 emissions annually. If indirect emissions are considered, then industry accounts for almost 40% of global anthropogenic CO_2 emissions. [35]

Approximately 1.9 billion tonnes of annual CO_2 emissions from industry are process emissions where carbon dioxide is produced as a bi-product of chemical reactions inherent to the production process. These emissions cannot be avoided by changing the energy source. The only feasible option for their mitigation in many cases is to remove the CO_2 after production using CCS. For example, 65% of emissions from the production of cement arise from the chemical reaction in which calcium carbonate (limestone) is converted to calcium oxide (lime). It is not possible to avoid the production of CO_2 in cement production.

Other examples of industrial processes with significant CO_2 emissions are natural gas processing, iron and steel production, ammonia/urea production, biofuel production, and various petrochemical processes that produce chemicals, plastics and fibers.

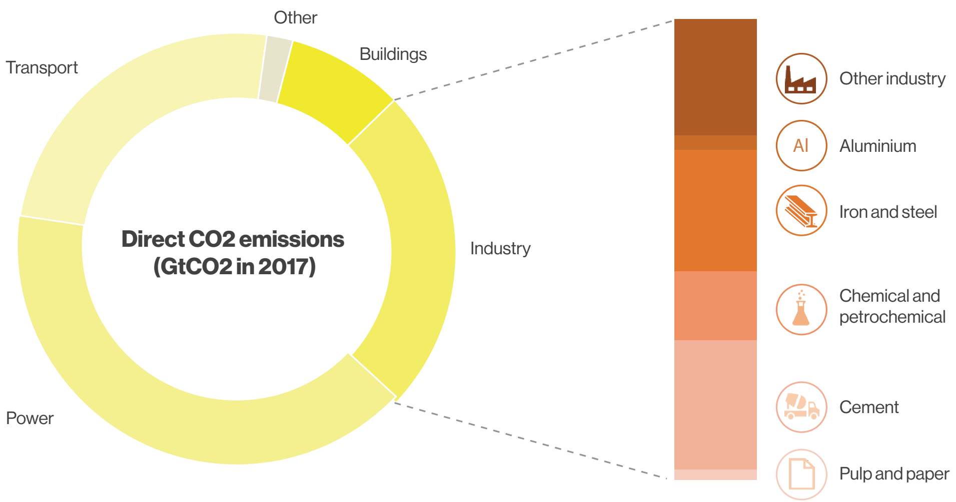

Figure 18. Global Direct CO_2 Emissions by Sector [36]

[35] IEA, 2019 Transforming Industry through CCUS.

[36] Global CCS Institute Analysis of IEA data.

Demand for these industrial products will grow at least through the middle of this century driven by an additional 2 billion people to feed, clothe, house, transport and entertain. Demand growth will also be driven by growing affluence particularly in developing economies where hundreds of millions of people will be able to afford to purchase goods and services, requiring these inputs, for the first time.

Experience over the last decade is informative. Steel production capacity increased by 18% between 2010 and 2018.[37] Clinker (for cement) production capacity increased by 19% between 2010 and 2019.[38] In both cases, capacity additions were dominated by developing countries, particularly China and India.

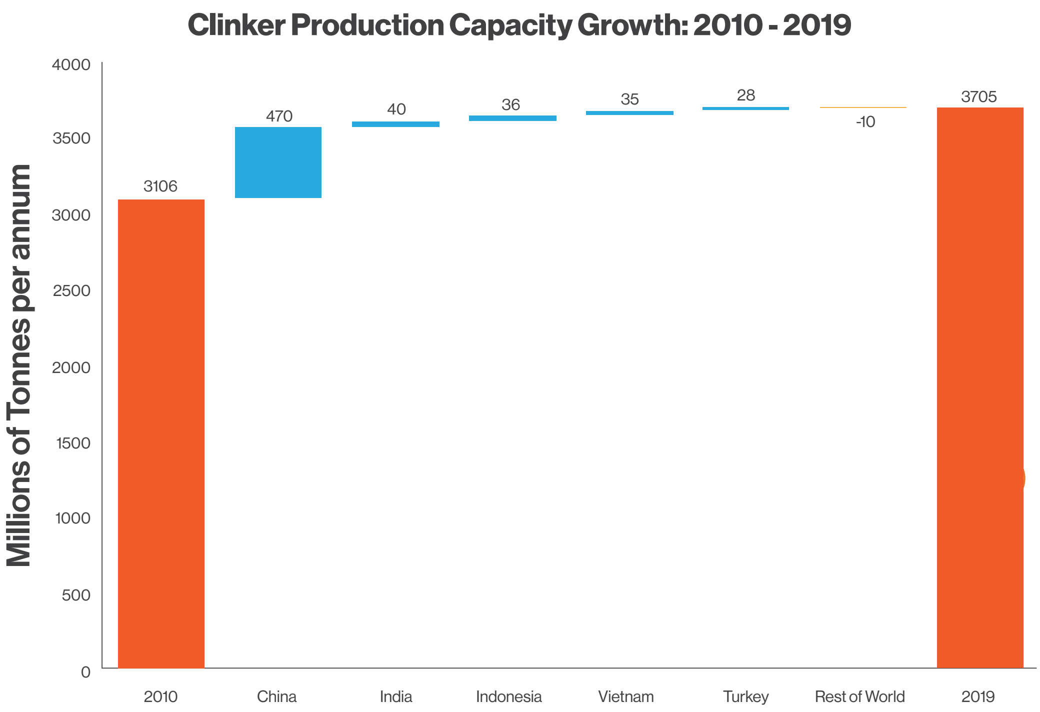

Figure 19. Clinker Production Capacity Growth 2010 to 2019

[37] OECD Steelmaking Capacity Database.

[38] USGS Mineral Commodity Summaries (2012 and 2020).

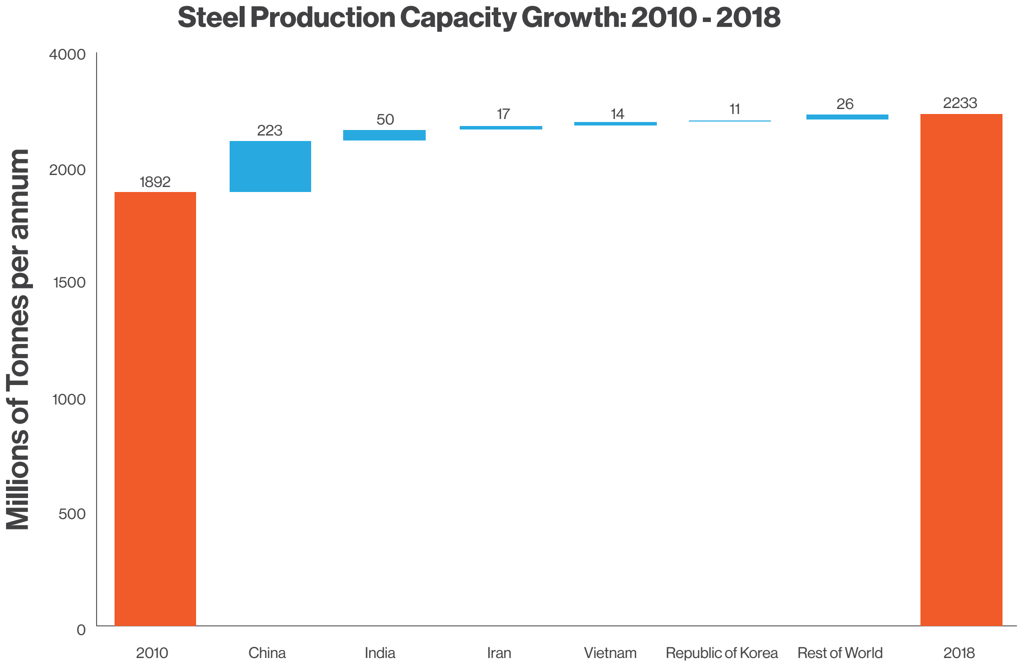

Figure 20. Steel Production Capacity Growth: 2010 - 2018

Considering current commitments in Nationally Determined Contributions to limit emissions and improve energy efficiency, the International Energy Agency estimates that direct emissions of CO_2 from Industry will grow from 8 billion tonnes per annum to almost 10 billion tonnes per annum by 2060. To achieve a climate outcome consistent with the Paris Agreement, direct emissions from industry must instead fall to 4.7 billion tonnes of CO_2 per annum by 2060.[39]

Several approaches will be necessary to achieve these emissions reductions including fuel switching, improvements in energy efficiency, and the deployment of current best available technologies and future innovative technologies. CCS is one of the necessary approaches, making the largest contribution to emissions reduction in the cement, iron and steel, and chemicals sectors which currently constitute about 70% of direct emissions from industry.

[39] IEA, 2019: Transforming Industry Through CCUS.

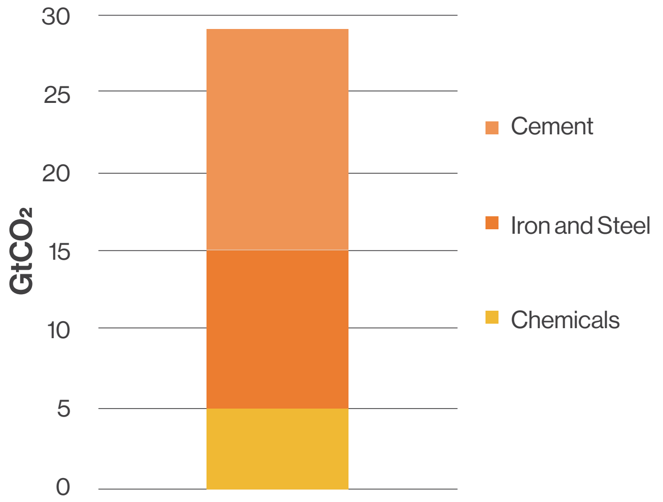

Figure 21. CCS Contribution to Emission Reduction in the Cement, Iron & Steel and Chemicals Sectors between 2017 and 2060.[23]

The International Energy Agency estimates that 29 billion tonnes of abatement must be provided by CCS between 2017 and 2060 in these three sectors to achieve a climate outcome consistent with the Paris agreement. CCS has the largest role in the chemicals industry, delivering 14 billion tonnes of abatement to 2060 due to several chemical production processes producing almost pure streams of CO_2 with a low capture cost.

CCS and Clean Hydrogen Production

Near-zero emissions hydrogen has the potential to make a significant contribution to emissions reduction in the power generation, transportation, and industrial sectors. Hydrogen can be burned in turbines or used in fuel cells to generate electricity, can be used in fuel cells to power electric vehicles, as a source of domestic and industrial heat, and as a feedstock for industrial processes. The virtue of hydrogen is that it produces zero carbon emissions at the point of use.

In 2018, around 70Mt per annum of pure hydrogen was used, almost entirely for refining (38Mt) and the production of ammonia (31Mt). Less than 0.01Mt of pure hydrogen was used in fuel cell electric vehicles. In addition to pure hydrogen, an additional 48Mt of hydrogen mixed with other gases (mostly carbon monoxide in the form of syngas) was used for industrial heat (26Mt), methanol production (12Mt), and Direct Reduction Iron production (4Mt). Currently, 98 per cent of global hydrogen production is from unabated fossil fuels, around three quarters from reforming of natural gas and the rest from gasification of coal. The remaining 2% of hydrogen is produced using electrolysis.[40] Current hydrogen production is emissions intense, emitting around 830Mtpa. [41]

[40] International Energy Agency (2019), The Future of Hydrogen, Seizing today's opportunities, International Energy Agency, Paris, available at < https://www.International Energy Agency.org/hydrogen2019/>.

[41] Global CCS Institute (2019b), 'CO2RE Database, Climate Change Report', accessed from <https://CO2RE.co/ClimateChange>.

For hydrogen to make a meaningful contribution to global greenhouse gas emission reductions, very large quantities of hydrogen will need to be produced to displace a significant proportion of current unabated fossil fuel use. Annual demand for hydrogen could grow to 530Mt by 2050, reducing annual CO_2 emissions by up to 6 billion tonnes.[42] However that abatement benefit requires that hydrogen is produced using near zero emission processes such as electrolysis powered by nuclear or renewable electricity or from gas, coal or biomass with CCS. Currently, less than 0.7% of hydrogen production is from renewable energy (via electrolysis) and fossil fuel plants equipped with CCS.[43]

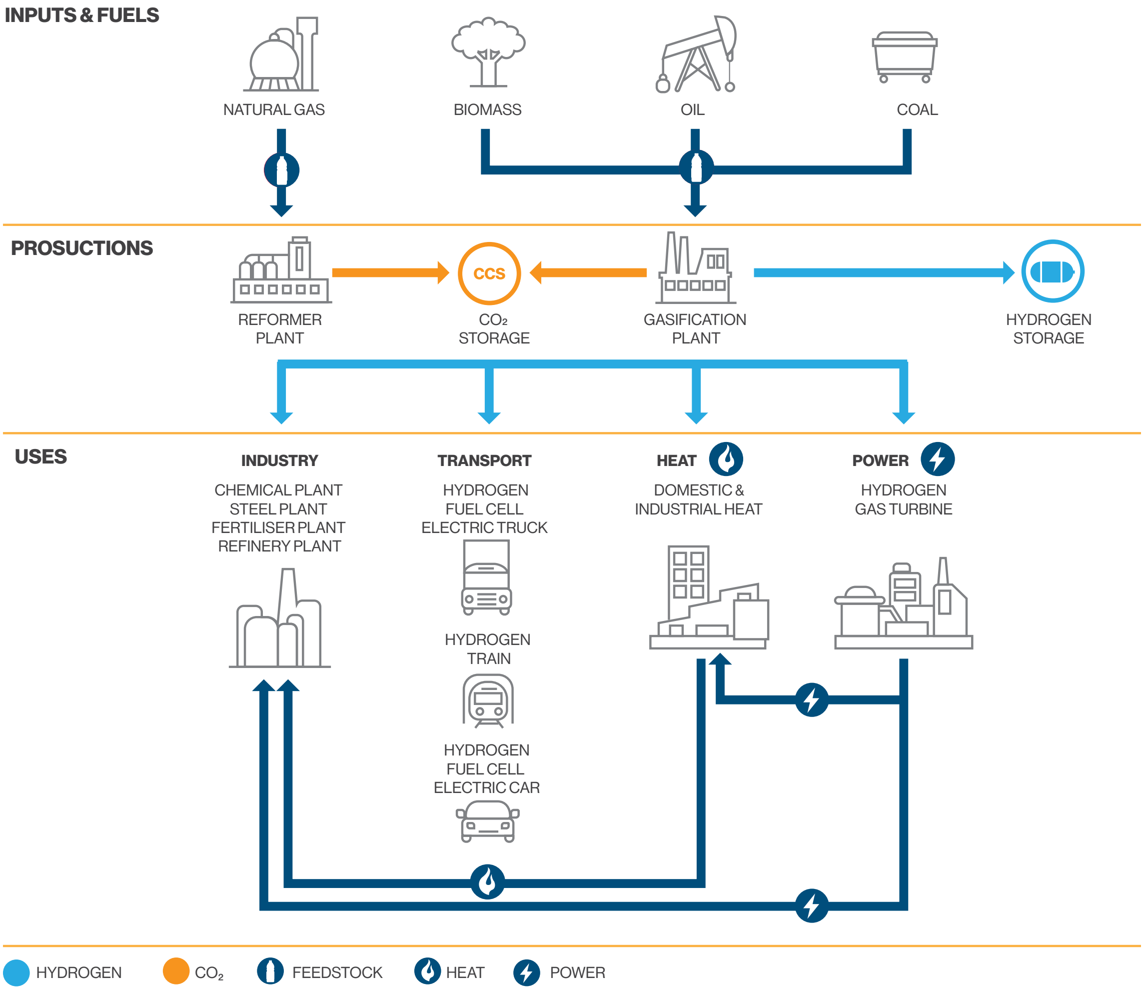

Figure 22. Hydrogen in the low emissions economy.

[42] Hydrogen Council (2017), Hydrogen scaling up, A sustainable pathway for the global energy transition, available from www.hydrogencouncil.com

[43] International Energy Agency (2019), The Future of Hydrogen, Seizing today's opportunities, International Energy Agency, Paris, available at < https://www.International Energy Agency.org/hydrogen2019/>.

The ability to rapidly scale up clean hydrogen production is a critical success factor. In this respect, scaling up production of clean hydrogen from fossil fuels with CCS is relatively simple. Coal, methane and pore space for CO_2 storage are plentiful and the technology is proven at large scale. Hydrogen has been produced through gas reforming or coal gasification with CCS for decades. For example, the Great Plains Synfuel Plant in North Dakota, US, commenced operation in the year 2000 and produces approximately 1,300 tonnes of hydrogen (in the form of hydrogen rich syngas) per day, from brown coal. In comparison, the largest operating renewable powered electrolyser in Fukushima Japan can produce around 2.4 tonnes of hydrogen per day.[44] There are five low-carbon hydrogen production facilities with CCS operating and one under construction, with a total annual production capacity of 1.5 million tonnes of hydrogen.

Table 2. Hydrogen production facilities with CCS[45]

Facility	H_2 Production Capacity	H_2 Production Process	Operational Commencement
Enid Fertiliser	200 tonnes per day of H_2 in syngas	Methane reformation	1982
Great Plains Synfuel	1,300 tonnes per day of H_2 in syngas	Coal gasification	2000
Air Products	500 tonnes H_2 per day	Methane reformation	2013
Coffeyville	200 tonnes H_2 per day	Petroleum coke gasification	2013
Quest	900 tonnes H_2 per day	Methane reformation	2015
Alberta Carbon Trunk Line - Sturgeon	240 tonnes H_2 per day	Asphaltene residue gasification	2020
Alberta Carbon Trunk Line - Agrium	800 tonnes H_2 per day	Methane reformation	2020
Sinopec Qilu	100 tonnes H_2 per day (estimated)	Coal/Coke gasification	Expected 2021

[44] Assuming solar PV capacity factor of 0.25 for 20MW PV capacity, 10MW electrolyser and 50kWh per kg of H_2 produced.

[45] GCCSI CO_2RE Database.

There is a large range of costs of production of clean hydrogen for both fossil fuels/biomass with CCS and renewable powered electrolysis. Key determining factors of cost are the price of coal, gas or biomass and the quality of the CO_2 storage resource for fossil/biomass hydrogen with CCS, and the quality of the renewable energy resource (which impacts electricity price & capacity factor of the elctrolysers) for renewable hydrogen. Overall, hydrogen produced from coal or gas with CCS is the lowest cost clean hydrogen today and is expected to remain so at least until 2030.[46] However there will be locations with oustanding renewable energy resources and where there is no opportunity for that renewable electricity to displace unabated fossil generation, where production of renewable hydrogen using electrolysis will be competitive. In these circumstances renewable hydrogen can make an important contribution and must be pursued. However, achieving meaningful scale in renewable hydrogen is challenged by the fundamental physics of this process. To illustrate, meeting potential future global clean hydrogen demand of 530 million tonnes per year using electrolysis would require more than 26,000 TWh[47] of electricity, which is approximately equal to the total electricity generated by all sources combined in 2018.[48]

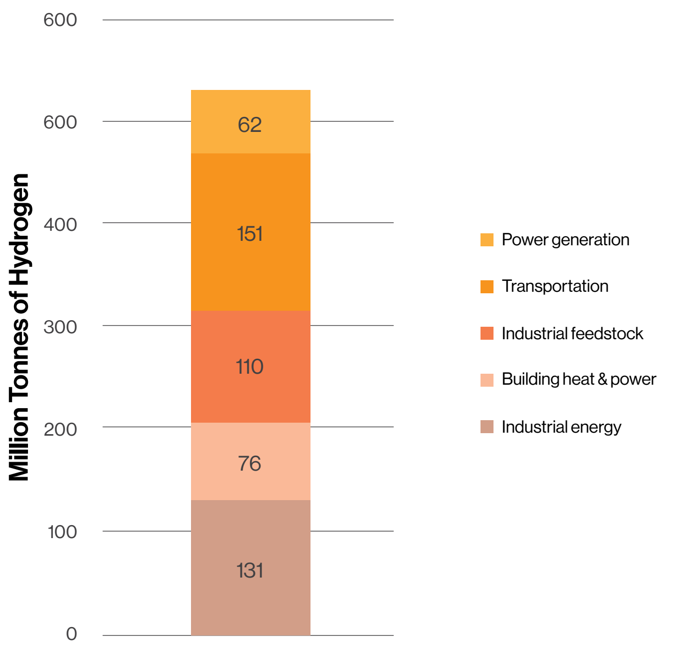

Figure 23. Potential annual global hydrogen demand in 2050.[49]

[46] IEA 2019.The Future of Hydrogen, Seizing today's opportunities.

[47] Assuming 50kWh of electricity per kg of H_2 produced.

[48] IEA 2019, World Energy Outlook 2019.

[49] Adapted from Hydrogen Council (2017), Hydrogen scaling up, A sustainable pathway for the global energy transition, available from www.hydrogencouncil.com

Emissions Abatement Opportunity Cost of Using Renewable Electricity to Produce Hydrogen

There is a significant emissions abatement opportunity cost associated with using renewable electricity to produce hydrogen instead of using that same quantity of renewable electricity to displace unabated fossil fuel generation from the electricity grid. Consider using clean hydrogen produced using renewable electricity powered electrolysers to displace the combustion of natural gas. The ratio of the emissions abatement from direct use of renewable electricity to displace grid generation, to the emissions abatement from the displacement of natural gas by hydrogen produced using the same quantity of renewable electricity can be calculated as follows.

Er =	energy value of the renewable electricity in GJ
Ac =	emission abatement if renewable electricity is used to displace grid generation in tonnes CO_2e
Ag =	emission abatement if renewable electricity is used to produce hydrogen which then displaces combustion of natural gas in tonnes CO_2e
PEMeff =	efficiency of conversion of electrical energy to hydrogen in electrolysers: 0.71 (converted from 55kWh/kgH_2 - HHV)
EFc =	Emissions intensity of grid generation displaced in kg CO_2e/GJ
EFg =	Emission factor for natural gas combustion: 51.53kg CO_2e/GJ

$$\frac{Ac}{Ag} = \frac{Er * EFc}{Er * PEMeff * EFg}$$

$$Ac = \left(\frac{EFc}{PEMeff * EFg}\right) * Ag$$

Substituting values for variables:

$$Ac = \left(\frac{EFc}{0.71 * 51.53}\right) * Ag$$

This relationship is graphed in Figure 24.

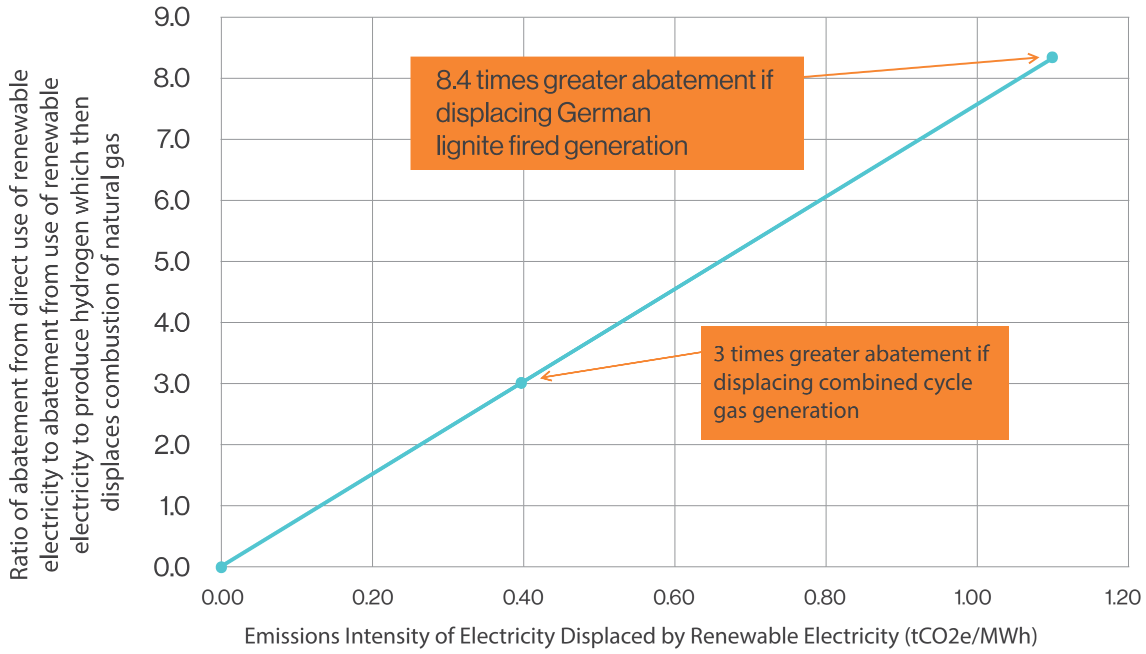

Figure 24. Relationship between abatement from direct use of renewable electricity to displace fossil generation and abatement if renewable electricity is used to produce hydrogen which then displaces the combustion of natural gas.

Renewable electricity provides the greatest climate benefit when used directly as electricity to displace unabated fossil generation. For example, using renewable electricity to displace electricity generated from German lignite would deliver eight times more emissions abatement than using that same quantity of renewable electricity in electrolysers to produce hydrogen which then displaces the combustion of natural gas. Even if the renewable electricity only displaces electricity generation from combined cycle natural gas, it would still deliver three times more abatement. The alternative which delivers far greater overall emissions abatement is to produce clean hydrogen from natural gas or coal with CCS and use renewable electricity in the grid.

05

Barriers

Barriers

Carbon capture and storage technologies are commercially available and have been proven at large scale over the past five decades. Geological storage resources are more than sufficient to meet CO_2 storage requirements under any scenario to achieve ambitious climate targets. In summary, there are no technological or resource barriers to broadscale deployment of CCS. Yet CCS is not being deployed at the rate necessary to stabilize the global climate. The same can be said of renewable energy, nuclear power, electric vehicles, and a myriad of other low emissions and energy efficiency technologies.

The reason that these essential technologies including CCS are not being deployed at the necessary rate is that the incentive for investment is insufficient to mobilize the requisite capital. There are several market failures across the CCS value chain that directly affect the business case for CCS, as summarized in Figure 25.

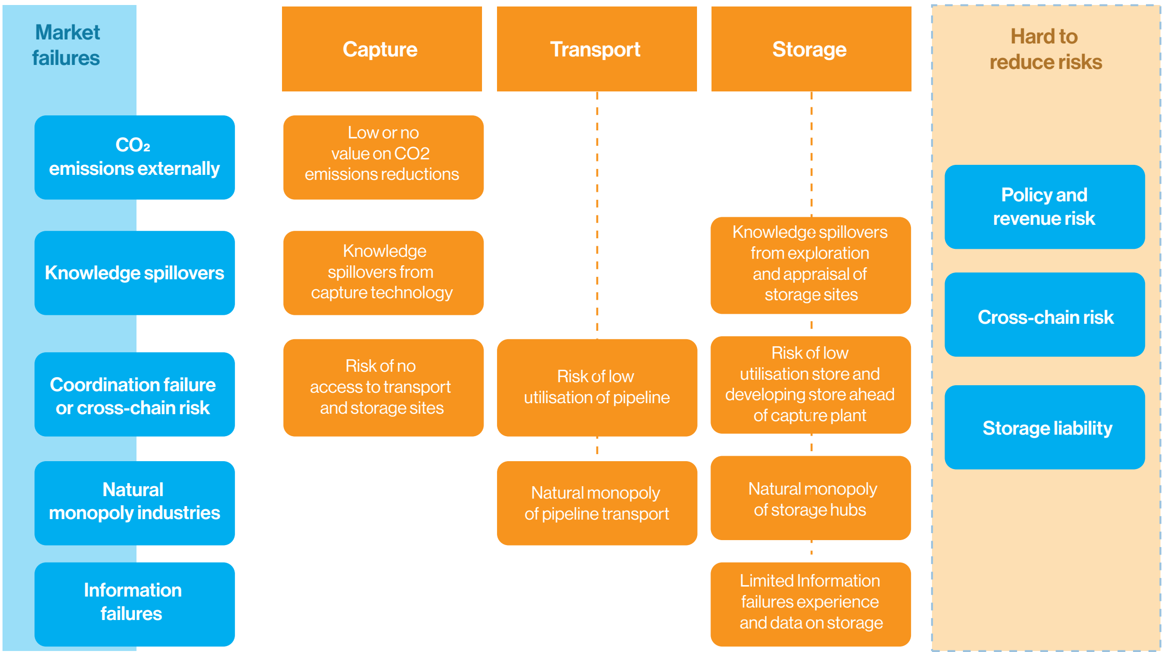

Figure 25. Market Failures across the CCS value chain

For a potential capture plant developer, the main impediment to investment is the lack of a sufficient value on emissions reductions. Without this, there is no incentive for a developer to incur the costs of constructing and operating the capture plant, even though it may be beneficial from a broader societal perspective in helping to meet climate targets cost effectively. In economic terms, CO_2 emissions are an externality.

Whilst capture technologies are well developed and proven, their application in most industries has been very limited and investment to date, for the most part, has been by first movers. First movers incur additional costs through the application of conservative engineering to ensure the successful integration of the capture plant with the host plant. The developers of the Boundary Dam and Petra Nova CCS facilities have both stated that the capital cost of building their plant again could be reduced by at least 20% simply by applying what was learned the first time. In fact, an approximate 20% reduction in capital cost per unit CO_2 capture capacity was observed between Boundary Dam in 2014 and Petra Nova in 2017.

First movers are also the first to test business models and regulations, especially if the project is in a jurisdiction in which CCS has not previously been undertaken. This particularly applies to geological storage resource operators who must navigate geological storage regulations or find a way to manage access to pore space, compliance and liability risk if the regulation is absent or unclear. The second operator in a jurisdiction will have the benefit of precedent and a more informed and confident regulator not enjoyed by the first. Fast followers can take advantage of the learnings for which first movers have paid. These knowledge spillovers create an incentive to delay investment in CCS projects until there is greater experience on which to base business decisions.

The CCS value chain requires a broad range of skills and knowledge. Perhaps with the exception of natural gas separation, competencies required for the handling and transport of dense phase gases or the appraisal and operation of geological storage facilities are beyond the capture plant operator. Similarly, CO_2 separation and capture is often well beyond the competence of the host plant operator. For example, a cement manufacturer has no expertise in CO_2 capture, transport or geological storage. Thus in most circumstances, the most efficient value chain will involve multiple parties each specializing in one component of the value chain and the CCS project will require coordination of multiple investment decisions which all have long lead times. Once the CCS project is operating, the interdependency between value chain actors remains. The storage operator relies upon the capture operator to supply CO_2 and vice versa. If any element of the chain fails, the whole chain fails. This creates cross-chain risk.

The transport and storage elements of a CCS value chain will in many if not most cases be natural monopolies which creates a risk of price gouging for the services they offer. In the absence of competitors, they are able to set their price at the highest level that their customers can bear, eroding the business case for investing in a capture project.

There are also information failures arising from the limited experience in developing and operating CCS value chains. One example relates to geological storage of CO_2. Whilst geological storage of CO_2 is well understood and has been proven through decades of experience and a massive body of scientific study, there is still only a very small pool of commercial operational data compared to other industries. This translates to an increased perception of risk amongst financiers and investors.

Capital intensive investments like CCS are exposed to many classes of risk. Most of these risks are best managed by the value chain actors. Project operators are best placed to manage operational and safety risks for example, as is the case across mature heavy industries. There are also 'hard to manage' risks that the private sector is unwilling or unable to take on. These risks are usually managed through government policy and regulation. For example, corporate law provides a general framework for undertaking business that significantly reduces the risk of undetected dishonest behavior by counterparties. For CCS, which is an immature industry, there are three specific hard to manage risks:

- Policy and revenue risk
- Cross chain risk
- CO_2 storage liability risk

The policy and revenue risk arises because there is no natural market for the storage of CO_2. Policy or regulation is required to correct the CO_2 externality to support revenue generation (or the avoidance of costs) essential to the business case for investment. The cross-chain risk is linked to the immaturity of the CCS industry and the lack of confidence that exists in business models and between counterparties compared to mature industries. The CO_2 storage liability risk is related to potential perpetual liability for regulatory enforcement action, exposure to future carbon pricing and civil claims for damages arising from leakage of CO_2 from geological storage facilities. Whilst the probability of leakage from an appropriately selected and operated geological storage facility is diminishingly small, it is not zero. Taken together, these 'hard to manage risks' can be insurmountable barriers to investment. The difference in the cost of capital (debt and equity) between an investment that is perceived to have low risk versus an investment that is perceived to have high risk can be 10% or more. That risk premium can add several tens of millions of dollars to the annual cost of servicing debt for a CCS project, impairing the investability of the project.

Overall, the well-established and familiar business models, structures and practices that exist in mature industries and play a significant role in reducing perceived investment risk have generally not yet developed for CCS. In the large majority of cases, the market does not provide sufficient reward for CCS to achieve required rates of return on investment – and the required rate of return is usually elevated due to the perceived risk associated with the investment making financing difficult.

All things considered, it is clear that the primary barrier to the deployment of CCS at the rate and scale necessary to achieve climate targets is the difficulty in developing a project that delivers a sufficiently high risk-weighted return on investment to attract private capital.

06
Enabling policies

Enabling policies

The multiple market failures that create barriers to investing in CCS require a comprehensive and well designed policy framework. That framework must assist in reducing costs, support stable and predictable long-term revenues, and allocate risks to the party who is best placed to manage them. The objective should be to enable the CCS value chain to operate as efficiently as possible, incentivize private sector investment, and achieve climate mitigation targets at least cost to society.

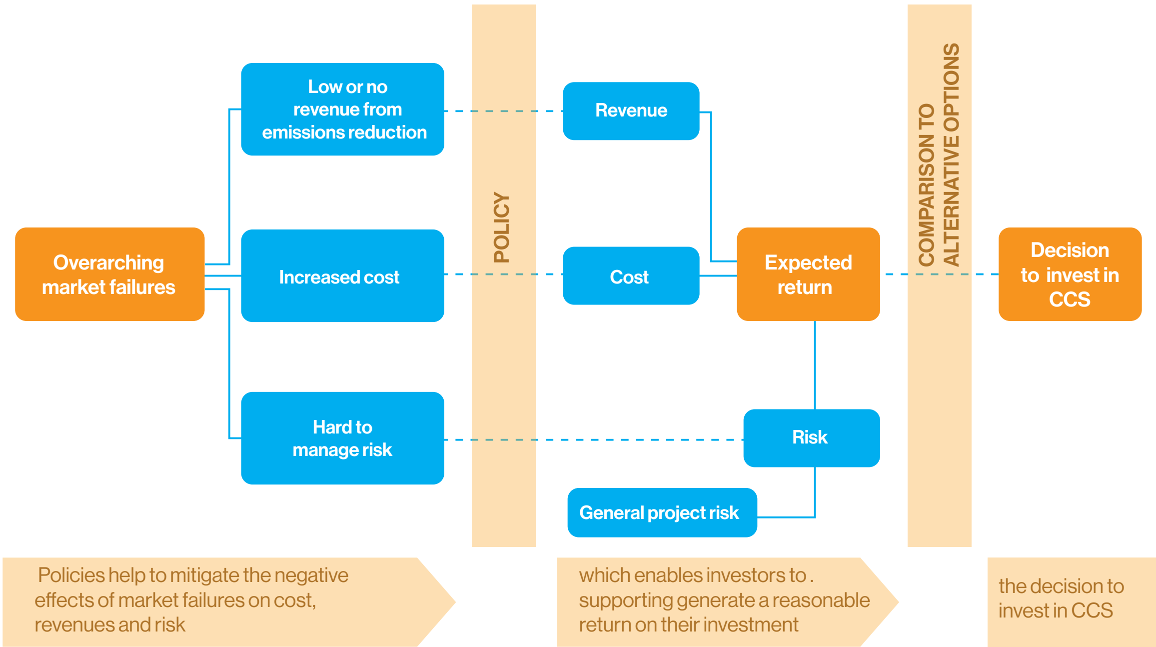

Figure 26. The role of policy in incentivizing investment in CCS

Despite these barriers to investment, there are circumstances where specific policies and commercial opportunities have enabled investment. Twenty-four commercial CCS facilities are either operating or in construction, all having made a positive financial investment decision. The enablers differ from project to project but there are some common features across these investments.

CCS Facility	Carbon Tax	Tax Credit or emissions credit	Grant support	Provision by government or SOE	Regulatory requirement	Enhanced oil recovery	Low cost capture	Low cost transport and storage	Vertical integration
US									
Terrell						○	●	●	
Enid Fertiliser						○	●	●	
Shute Creek					●	○	●	●	
Century Plant		●				○	●		
Air Products SMR		●	○			○			
Coffeyville		●				○	●		
Lost Cabin		●				○	●		
Illinois Industrial		●	○				●	●	●
Petra Nova[50]		●	○			○			
Great Plains						○	●		
ZEROS Project"		●				○			
Canada									
Boundary Dam			○	●	●	○		●	
Quest		●	○						●
ACTL Agrium			○			○	●		
ACTL Nutrien			○			○	●		
Brazil									
Petrobras Santos				●		○	●	●	
Norway						○			
Sleipner	●			●			●	●	●
Snohvit	●			●	●		●		●
UAE									
Abu Dhabi CCS				●		○		●	
Saudi Arabia									
Uthmaniyah				●		○	●	●	
China									
CNPC Jilin				●		○	●	●	●
Sinopec Qilu*				●		○	●	●	
Yanchang				●		○	●		
Australia									
Gorgon					●		●	●	●

Figure 27. Summary of policy and commercial enablers of investment in CCS facilities[51]

[50] Petra Nova has temporarily suspended operation due to low oil price.

[51] GCCSI, 2019. Policy Priorities to Incentivise Large Scale Deployment of CCS.

A Value on CO_2 Emission Reduction – Financial Reward

Of the 24 CCS facilities currently in operation or under construction, 19 sell or utilise CO_2 for EOR. The sale of CO_2 or utilisation for EOR provides a stable and predictable long-term source of revenue. That revenue stream may be sufficient to cover the costs of capturing and transporting CO_2 where capture costs are low, such as in natural gas processing, fertiliser and bioethanol production. This was the case at the Terrell, Enid Fertiliser and Great Plains CCS facilities. CO_2-EOR has proven to be a significant value driver and enabler of investment in CCS, however to meet climate objectives other value drivers not dependant upon EOR are essential.

One proven example is Tax credits, which have been an important enabler of the six large-scale CCS facilities that have commenced operation in the USA since 2011. In the USA, tax credits are issued under section 45Q of the Internal Revenue Code. The credits can be used to reduce a company's tax liability or, if they have no tax liability, can be transferred to the company that disposes of the CO_2 or can be traded on the tax equity market. Tax credits have the benefit of being well established in the context of climate change mitigation in the USA, having been used to drive significant investment in renewables over the past two decades. They provide a predictable effective revenue stream for each tonne of CO_2 stored (or utilized).

The recent extension and increase in the value of the 45Q tax credit has incentivized the next wave of CCS investments in the USA, with more than ten new projects currently progressing through feasibility or front end engineering and design studies.

TYPE OF CO_2 STORAGE/ USE	MINIMUM SIZE OF ELIGIBLE CARBON CAPTURE PLANT BY SIZE ($KtCO_2$/YR)			RELEVANT LEVEL OF TAX CREDIT GIVEN IN OPERATIONAL YEAR (USD/tCO_2)									
	POWER PLANT	OTHER INDUSTRIAL FACILITY	DIRECT AIR CAPTURE	2018	2019	2020	2021	2022	2023	2024	2025	2026	LATER
DEDICATED GEOLOGICAL STORAGE	500	100	100	28	31	34	36	39	42	45	47	50	
STORAGE VIA EOR	500	100	100	17	19	22	24	26	28	31	33	35	INDEX
OTHER UTILISATION PROCESSES *	25	25	25	17	19	22	24	26	28	31	33	35	

*Each CO_2 source cannot be greater than 500 $ktCO_2$/yr. Any credit will only apply he portion of the converted CO_2 that can be shown to reduce overall emissions.

Figure 28. The 45Q Tax Credit[52]

[52] Adapted from Bennet, S. and Stanley, T. (2018), Commentary: US budget bill may help carbon capture get back on track, International Energy Agency, Paris, available at: <https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-helpcarbon-capture-get-back-on-track.html>.

A Value on CO_2 Emission Reduction – Financial Penalty

Another approach to placing a value on each tonne of CO_2 stored is to establish a financial penalty for each tonne of CO_2 emitted. For example, a carbon tax introduced in Norway in 1991 incentivised the development of the Sleipner and SnØhvit CCS projects.

Regulation has played a role in incentivising investment in CCS by proscribing emissions above a certain level, which is effectively a financial penalty for emitting CO_2 equal to the total present value of the project. Chevron recognised the need to reduce CO_2 emissions from its Gorgon LNG project in Australia and included CCS in its Environmental Impact Statement. The approval of the project by the Western Australian Government subsequently included a mandatory condition to inject at least 80% of the reservoir CO_2 produced by the gas processing operations. Gorgon is the world's largest dedicated CO_2 storage facility with a capacity of 4 million tonnes of CO_2 per year.[53]

The introduction of an emissions performance standard (EPS) for power generation in 2011 in Saskatchewan was a driver of the development of the Boundary Dam CCS facility. Without CCS, the Boundary Dam coal unit would have been required to close and be replaced by a natural gas combined cycle plant (NGCC).

Financial penalties and regulation must be applied with caution to prevent perverse outcomes such as the movement of production capacity, and its associated emissions, to another jurisdiction with less stringent climate policy. Financial penalties and regulation must meet the following two criteria to be successful:

- any financial penalty must be set materially higher than the cost to the regulated facility of capturing and storing CO_2, and
- the cost to the regulated facility of capturing and storing CO_2 must not threaten the commercial viability of the facility

[53] Chevron, 2018. Fact Sheet Gorgon Carbon Dioxide Injection Project; The world Gorgon Carbon Dioxide Project. [Online] Available at: https://australia.chevron.com/-/media/australia/publications/documents/gorgonco$_2$-injection-project.pdf

These conditions were met in the three examples provided. At $17/t$CO_2$, the cost of injecting and storing CO_2 for the Sleipner project was much less than the $33/t$CO_2$ tax penalty at the time for CO_2 vented to the atmosphere.[54,55] The current level of the tax is higher than when it was introduced, making the business case for CCS at Sleipner even stronger today.[56] At Gorgon, the additional capital costs of compressing and storing CO_2 were manageable in the context of the project as a whole, adding less than 5% to total project costs. At Boundary dam, the risk and cost of exposure to natural gas prices, which were much higher at the time and expected to remain so, made refurbishment and application of CCS to the coal unit the commercially rational decision.

Capital Grants

Bringing new technologies to market is challenging because they are beset by the 'technology valley of death' where financing is difficult to obtain for innovations that are technically proven but not yet commercialised.[57] Grant funding reduces the private capital requirement and thereby increases the return on private capital enabling investment. It also mitigates the disincentive to be a first mover by rewarding them for the knowledge they create that can be used by future project developers. Figure 29 shows the contribution of grant funding to the capital structure of a selection of CCS facilities.

[54] Herzog, H., 2016. Lessons Learned from CCS Demonstration and Large Pilot Projects, Massachusetts: Massachusetts Institute of Technology.

[55] Massachusetts Institute of Technology, 2016. Sleipner Fact Sheet: Carbon Dioxide Capture and Storage Project. [Online] Available at: https://sequestration.mit.edu/tools/projects/sleipner.html [Accessed December 2018].

[56] Price, J. P., 2014. Effectiveness of Financial Incentives for Carbon Capture and Storage, Virginia: Bluewave Resources LLC.

[57] Murphy, L. & Edwards, P., 2003. Bridging the Valley of Death: Transitioning from Public to Private Sector Financing, Colorado: NREL.

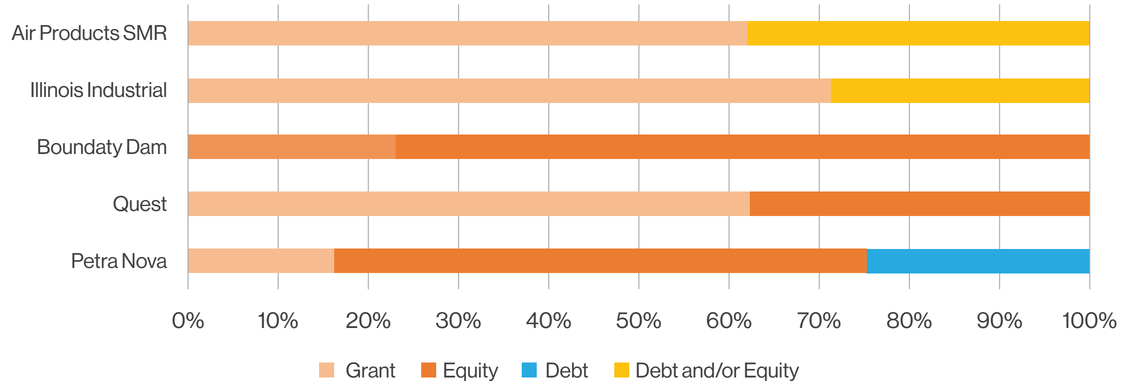

Figure 29. Capital Structure of Selected CCS Facilities[58]

Grant support has also been used to fund the construction of transport and storage networks, to address the cross-chain risk that capture plant developers are exposed to. This is the approach that has been adopted for the Alberta Carbon Trunk Line, which has received CAN$558M from the Alberta and Canadian governments for the CAN$1.2B project.[59] The 240km pipeline connects emitters in Alberta's industrial heartland with aging oil reservoirs in central and southern Alberta for use in EOR. The pipeline has been oversized for the first phase of the project, such that the volume of CO_2 transported can increase over time as more emitters invest in capturing CO_2 and utilise the transportation network. At full capacity, the pipeline will be able to transport 14.6 $MtCO_2$ per year, making it the largest EOR project in the world.

Facilitating CO_2 Transport and Storage Infrastructure

There are many examples where government support, or direct investment was required to de-risk and initiate the development of new industries including road, rail, telecommunications, electricity generation and distribution, space exploitation and more recently, renewable energy. As those industries have matured and become commercial, government intervention has been replaced by private sector investment. The equivalent opportunity for CCS, is to support the establishment of CO_2 transport and storage networks that can service industrial CCS hubs.

CCS hubs significantly reduce the unit cost of CO_2 storage through economies of scale and offer commercial synergies that reduce the risk of investment. The colocation of industries and firms within a region creates an industrial ecosystem that benefits all firms. CCS hubs reduce counterparty or cross chain risks as they provide capture and storage operators with multiple customers/suppliers.

[58] GCCSI, 2019. Policy Priorities to Incentivise Large Scale Deployment of CCS.

[59] Natural Resources Canada, 2013. Alberta Carbon Trunk Line (ACTL).

A CCS hub requires a geological storage resource for CO_2. Identifying and characterizing a storage resource requires the investment of tens to hundreds of millions of dollars, all of which is at-risk as there is no guarantee of success. Unlike mineral or hydrocarbon exploration, in which billions of dollars of at-risk capital are invested annually, the return on investment for exploration for pore space does not generally justify investment. Government can assist in overcoming this barrier by supporting the collection of geological data and making it available. The current fleet of CCS facilities have benefitted from pre-existing geological data collected in the course of oil or gas exploration and/or from government funded programmes.

Establishing a CCS hub also requires that CO_2 transport infrastructure initially be oversized to accommodate future demand. This is a difficult proposition for the private sector as it involves knowingly investing in a capital-intensive asset that will have low utilization, and in a business that initially has high cross chain risk (until other businesses join the hub). Government can overcome these barriers to investment by co-investing in CO_2 transport infrastructure with the private sector to establish the CCS hub. Over time, other businesses will join the hub increasing the utilization of the infrastructure. When the hub is well established, government has the option of selling its equity to recoup its initial investment. The end result is a commercially sustainable CCS hub delivering material CO_2 emissions abatement whilst protecting and creating high value jobs and providing a just transition for host communities.

Establishing Transparent Regulation of CO_2 Storage and Long-Term Liability

Transparent and predictable regulation of access to pore space for the geological storage of CO_2 is essential. Investors must be confident that they can secure the right to exploit geological storage resources and manage compliance risk associated with CO_2 storage operations.

Further, it is critical for governments to implement a well-characterized legal and regulatory framework that clarifies operators' potential liabilities. An excellent example, where the storage operator bears the risk of short-term liability during the operational period of the project and for a specified post-closure period, has been implemented by the Australian Government. This is described below.

> "Following the completion of a period of at least 15 years, from the issue of the Site Closure Certificate, the title-holder may apply to the Minister for a declaration confirming the end of the "Closure Assurance Period". A declaration at the end of this period concludes the title-holder's liability for the storage site. Importantly, the Offshore Petroleum and Greenhouse Gas Storage Act also provides the former title-holder with an indemnity from the Commonwealth Government for any liability accrued after the Closure Assurance Period."[60]

[60] Havercroft, I., Dixon, T. & McCoy, S., 2015. Legal and Regulatory Developments on CCS. International Journal of Greenhouse Gas Control, pp. 431-448.

Access to Low Cost Capital

The cost of debt and equity has a material impact on the total project cost and financial viability of capital intensive investments, such as CCS facilities. Governments can reduce the cost of capital to CCS developments through various measures other than capital grants including:

- provision of low-cost loans and convertible loans
- loan guarantees
- direct investment (taking equity)

This is a proven strategy for attracting private capital to investments that would not otherwise meet hurdle rates. An example is the Clean Energy Finance Corporation (CEFC) established and capitalised by the Australian Government. The CEFC provides low cost finance to renewable energy and other sustainable economy related projects, and has attracted AUD26B of private sector investment through the provision of AUD5.5B of CEFC capital. [61]

Building Confidence and Public Support

Public confidence in, and understanding of the necessity of CCS in meeting climate targets is essential. The public discourse on CCS is often marred by misinformation, misunderstanding and ignorance. This undermines investor confidence, community support and the ability of governments to allocate scarce fiscal and political capital to CCS, and if remains unchecked, will prevent achievement of climate targets. It is absolutely essential that governments do the rigorous analysis necessary to clearly define the role of CCS in meeting their national emission reduction targets and communicate that to industry and the public.

The United Kingdom Committee on Climate Change provides an excellent example. In May 2019, the committee published its report; Net Zero, The UK's contribution to stopping global warming. This report describes how the UK can achieve net-zero emission by 2050. Their analysis demonstrates the need for every possible low emissions and energy efficiency technology and identifies the need for CCS to mitigate emissions from industry, power generation, hydrogen production and also through BECCS and DACS. The report identifies 179Mt of CO_2 must be captured and stored in the United Kingdom in 2050.

[61] www.CEFC.com

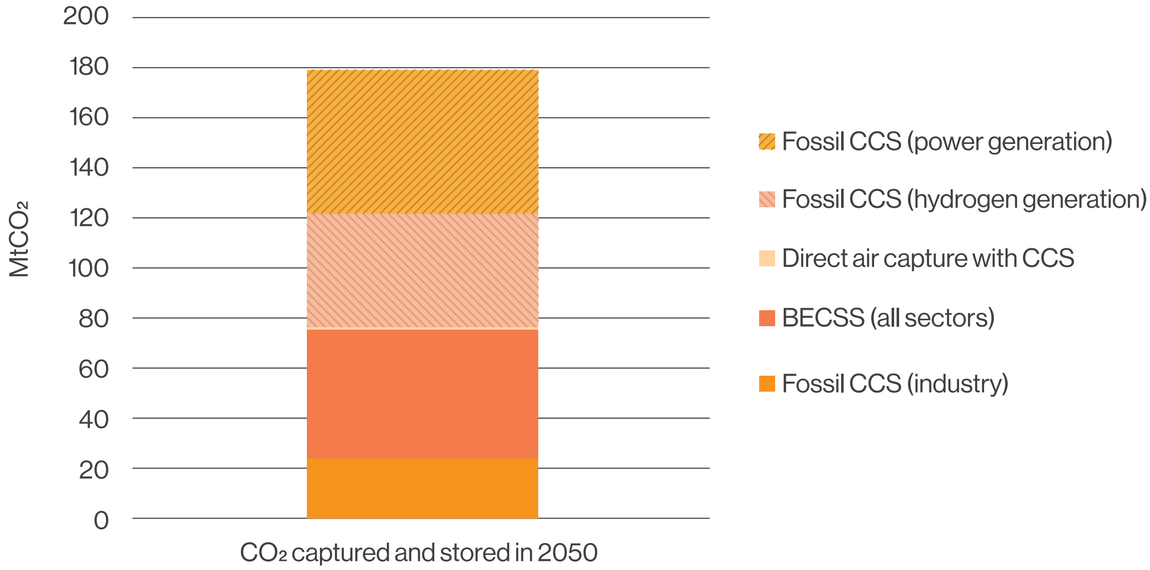

Figure 30. CO_2 Captured and Stored in the United Kingdom in 2050 to Achieve Net-zero Emissions[62]

Summary of Enablers of CCS without Revenue from EOR

As previously stated, EOR is an important enabler of investment in early CCS facilities however deployment well beyond opportunities provided by EOR is necessary to achieve climate targets. Table 3 summarises the key factors than enabled investment in the five operating commercial CCS facilities that do not rely upon EOR as a revenue source. They show how different combinations of policy and regulation (as described in the previous sections) and commercial conditions have facilitated investment in CCS without EOR revenues.

[62] Adapted from UK Committee on Climate Change, 2019. Net Zero. The UK's contribution to stopping global warming.

Facility	Support	Value on CO_2 or Regulation	Capture	Storage	Hard to Manage Risk
Gorgon	AUD60M (small contribution to studies)	CCS was a condition of approval of the EIS.	Very Low Cost Capture.	Leverage hydrocarbon exploration data.	Vertically integrated project - no cross chain risk. Liability transfer 15 years post injection. Clear Regulation.
Sleipner	Norwegian State owned at time of investment.	C tax was USD33/ tonne, now USD80/tonne.	Very Low Cost Capture.	Leverage hydrocarbon exploration data.	Vertically integrated project - no cross chain risk. Clear Regulation. State is a partner.
Snohvit	Norwegian State majority owned (71%) at time of investment.	CCS was a regulatory requirement plus C tax as per Sleipner.	Very Low Cost Capture.	Leverage hydrocarbon exploration data.	Vertically integrated project - no cross chain risk. Clear Regulation. State is a partner.
Quest	CAN$865M grant.	CAN$15-30 per tonne. 2 credits granted for each tonne stored.		Low cost storage – excellent reservoir characteristics.	Vertically integrated project - no cross chain risk. Liability transfers on successful closure. Clear Regulation.
Illinois Industrial	US$141M grant.	Tax credits; USD28/tonne CO_2 in 2018 rising to USD50/tonne in 2026.	Very Low Cost Capture.	US$66.7M for storage appraisal. Very low cost storage.	Vertically integrated project - no cross chain risk. Clear Regulation. Regulatory enforcement ends 50 years post injection.

Table 3. Summary of Success factors for CCS Investments without EOR Revenues

circular carbon economy