Carbon Capture and Storage: What is its role in climate mitigation?

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The Abdullah Bin Hamad Al-Attiyah International Foundation for
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INTRODUCTION

CARBON CAPTURE AND STORAGE: WHAT IS ITS ROLE IN CLIMATE MITIGATION?

The Paris Agreement on climate action, and the IPCC report on the impacts of warming of 1.5°C above pre-industrial levels, emphasise the importance of a range of different low carbon approaches in limiting dangerous climate change. What is the role of carbon capture and storage (CCS) in major studies of climate mitigation options? What is the global status of research, development and deployment of CCS technologies? How economically viable are CCS technologies? How far are we from enabling cost competitive deployment of CCS technologies in coal-fired power plants? What is the potential to further develop CCS technologies for their subsequent widespread use in all carbon-intensive industrial sectors?

Sustainability Report

This research paper is part of a 12-month series published by the Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent sustainable development topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed to members, partners and universities, as well as made available online to all Foundation members.

EXECUTIVE SUMMARY

- Carbon capture and storage (CCS), or carbon capture, use and storage (CCUS), is assessed by bodies such as the IPCC as one of the crucial methods for reducing carbon dioxide emissions, alongside energy efficiency, renewables, nuclear and land-use change.
- Scenarios cover a wide range, with some not making use of CCS at all, and others indicating that the application of CCS to limit warming to 1.5°C might require captured amount of 0.05-2 gigatonnes (Gt) CO2 per year by 2030 and 0.7-9.3 Gt/year by 2050 (The total global CO2 emissions in 2019 was about 33 Gt).
- The basic technology of CCS is quite mature, but substantial room remains for cost improvements. CO2-enhanced oil recovery (EOR) is also well-established, while most other large-scale uses of CO2 (cement, synthetic fuels, plastics, etc.) are in research or early commercial stages.
- CCS can be applied to power generation and to industries, such as, petrochemicals, steel, aluminium, and cement. The industrial use is gaining in importance as there are few other cost-effective and technically mature solutions for these sectors.
- With experience, capture costs could fall to $20/tonne CO2 for low-cost options and $40/tonne for medium-cost options, and these price levels are below the range of likely carbon prices and competitive with other large-scale mitigation options.
- Progress over the last decade has been steady but slow, rising to about 25 Mt per year in 2019. This needs to be scaled up 14 times in order to meet median climate scenarios for 2030.
- CCS has received much less policy support than other low-carbon options such as renewables and energy efficiency. Recent increases/introduction of carbon prices and tax credits in the EU and US could move CCS towards widespread economic viability.
- Direct Air Capture (DAC) or bioenergy with CCS (BECCS) are required in many climate scenarios to reduce atmospheric CO2 levels directly, as emissions are unlikely to fall fast enough through other methods.
- CCS and DAC are crucial technologies to assure a long-term sustainable role in the energy mix for oil and gas.

CARBON CAPTURE COVERS A WIDE SUITE OF TECHNOLOGIES

Carbon dioxide (CO2), which is the main anthropogenic greenhouse gas, is produced by combusting carbon-containing fuels (coal, peat, oil, natural gas), by land clearance and deforestation, and by the decomposition of limestone in cement manufacture.

Carbon capture and storage (CCS) or carbon capture, use and storage (CCUS), is a suite of technologies to capture CO2 from these processes and to store it safely for the long term in underground rock formations, or convert it into useful products or stable minerals. Direct Air Capture (DAC) is CCS applied directly to the carbon dioxide in ambient air. Bioenergy with CCS (BECCS) uses CCS on a power plant burning biomass. Since the biomass has taken up CO2 as it grows, BECCS is a "negative emissions" method of reducing atmospheric CO2 concentrations.

CCUS involves three steps. Carbon dioxide is captured from a process. It is transported to where it is to be used, via pipeline or tanker. And it is stored or used.

There are a wide range of technologies available practically or potentially to capture carbon dioxide. From the power sector, there are three main groups of methods:

- Pre-combustion capture – the fuel is converted into a non-carbon containing energy carrier (such as hydrogen or ammonia), and the carbon dioxide is removed.
- Post-combustion capture – the fuel is combusted and carbon dioxide is separated from the flue gas, which is a mix of CO2 with nitrogen, water and other contaminants.
- Oxyfuel – the fuel is burnt in pure oxygen, so that the flue gas is a simple mix of water (which is easily removed) and CO2.

Industrial plants produce CO2 in various ways. Some yield a relatively pure stream of CO2 which can be readily captured – such as the removal of naturally-occurring CO2 from gas, and the manufacture of ethylene oxide, pulp and paper, hydrogen (steam reforming of natural gas), methanol, urea, synthetic fuels (gas- and coal-to-liquids), ethanol, the fluid catalytic cracker (FCC) of oil refineries, and direct reduced iron (DRI).

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Others, such as industrial boilers, steel blast furnaces, aluminium smelting and most of oil refineries yield CO2 that is dilute and/or in small streams from many different parts of the respective plants. This significantly raises capture difficulty and cost.

The captured CO2 has various possible uses. Enhanced oil recovery (EOR), is by far the largest current use of CO2. In EOR, supercritical CO2 increases reservoir pressure, acts as a solvent, and significantly increases the amount of oil recoverable. CO2-EOR has been used in the US since the 1970s and is also employed on a large scale in Canada, the UAE and Saudi Arabia.

Other current uses for CO2 include agriculture (enhancing yields in greenhouses), in increasing the production of urea and methanol, and in hydraulic fracturing in oil and gas production as a substitute for water. Small-scale applications include medical, construction and welding, and food and beverages (in carbonated drinks and for decaffeination).

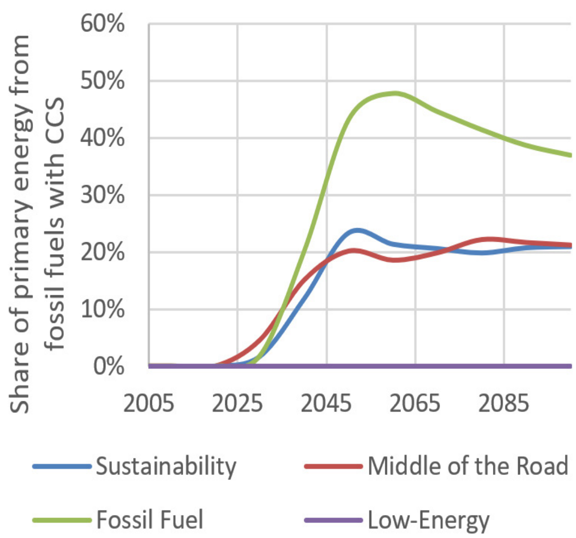
To raise the level of use of CO2 to the very large scale that is required to have an impact on GHG emissions, new applications would be required. These can include the manufacture of synthetic fuels; CO2-enhanced cement; soda ash; and various plastics and polymers.

CCS IS A MAJOR PART OF EMISSIONS MITIGATION IN MOST SCENARIOS TO LIMIT WARMING TO 1.5-2°C

The four Representative Concentration Pathways (RCPs) shown in the IPCC's report to be able to to limit global warming to no more than 1.5°C, all have different energy mixes.

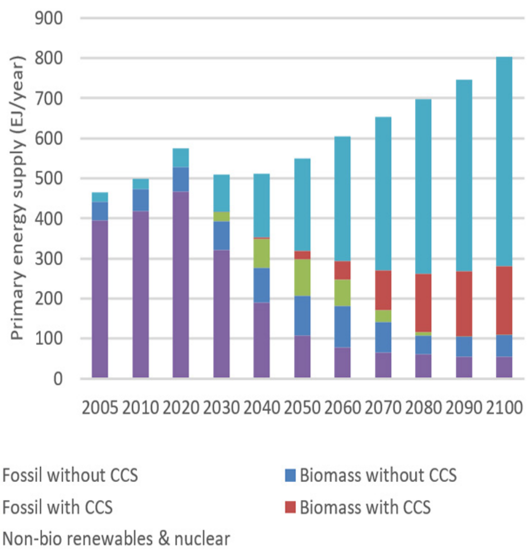
The four scenarios are shown in FIGURE 1: Sustainability (focussed on renewables), Middle of the Road (a mix of energy types), Fossil Fuel (a high use of fossil fuels) and Low-Energy (focussed on energy efficiency). Low-Energy does not include any use of CCS. Fossil Fuel includes an extremely high use of CCS, reaching almost 50% of primary energy, and mostly consisting of the use of BECCS to bring down atmospheric CO2 concentrations after overshooting. Sustainability and Middle of the Road have similar and quite high use of CCS, amounting to about 20% of primary energy use. In the three scenarios with CCS, it must be adopted very quickly during 2030-2050.

FIGURE 1 SHARE OF PRIMARY ENERGY WITH CCS, INCLUDING BIOMASS, 2005-2100 [i]



The energy mix breakdown in the Middle-of-the-Road scenario is shown in FIGURE 2. In this scenario, the use of fossil fuel CCS is progressively introduced between 2030-50, but is then phased out again. Biomass with CCS comes into play from 2050-2100, to mop up remaining fossil fuel emissions and draw down existing atmospheric CO2. Other low-carbon energy sources become the dominant contributor from about 2060 onwards.

FIGURE 2 ENERGY MIX IN THE MIDDLE OF THE ROAD SCENARIO



Because of its ability to tackle some emissions that are very hard to decarbonise otherwise, CCS reduces the overall cost of a mitigation portfolio. For instance, the IPCC found that excluding CCS as an option increased the discounted cost of limiting atmospheric CO2 to 450 parts per million (ppm) by 138%[ii].

CCS also improves the overall resilience of a climate-friendly portfolio, if for instance another option proves disappointing or unfeasible.

Different studies and scenarios provide a wide range of outlooks for CCUS over the century, ranging from zero to levels as high as about two-thirds of current annual emissions (TABLE 1).

TABLE 1 COMPARISON OF CCUS OUTLOOKS[iii]

Study	Fossil CO2 capture (Gt/year)			Biomass CO2 capture (Gt/year)		
	2030	2050	2100	2030	2050	2100
IPCC						
Low-Energy	0	0	0	0	0	0
Sustainability	0.5	4.9	2.0	0.006	1.4	3.2
Middle of Road	1.8	7.3	1.2	0.07	1.3	12.4
Fossil Fuel	0.1	0.7	0	0.6	16.1	22.5
Others						
GCCSI		2				
IEA SDSii	0.75	2.8				
IEA CCS Roadmapiii	2	7				
DNV	0.05	0.81				
Global Energy Outlookiv	0.2	9.3				

CCS IS A MAJOR PART OF EMISSIONS MITIGATION IN MOST SCENARIOS TO LIMIT WARMING TO 1.5-2°C

The comparison of CCS with other main low-carbon options: energy efficiency, renewables, nuclear, and land-use change (reforestation), is as shown in TABLE 2.

TABLE 2 COMPARISON OF CCS WITH OTHER LOW-CARBON OPTIONS

Option	Pro	Con
CCS	• Large-scale • Applicable to industry • Can draw down atmospheric CO2	• Slow adoption • Public, environmental dislike • Lacks business model in most places • Continuing other fossil fuel environmental impacts
Efficiency	• Low-cost • Public and political support	• Social barriers • Slow to implement on large scale • Does not eliminate need for low-carbon energy
	•	•
Nuclear	• Large-scale • Low land use • Dispatchable	• Safety concerns • Relatively expensive • Public opposition
Land-use change	• Ecosystem restoration • Draws down atmospheric CO2	• Vulnerable to reversal • Socially, politically complicated • Pressure on land for agriculture

Over the past decade or so, the emphasis in CCS has shifted from the power sector to industry. This is because of the rise of cheap gas in North America, undercutting the need for coal plants, and the major improvement in the cost and performance of solar and wind, which increasingly out-compete both coal and gas. Nevertheless, CCS remains an important technology for coal in some areas (such as Asia and Australia), and for gas in others (the Middle East).

CCS use in industry is growing in importance for three main reasons:

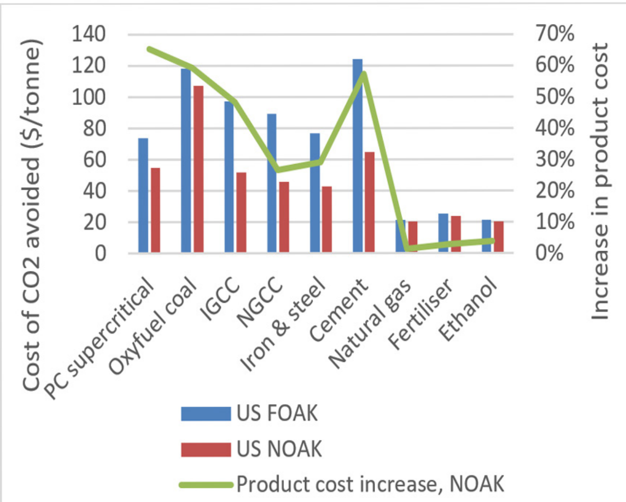
- Some industrial processes (cement, steel, petrochemicals) are very hard to decarbonise without CCS.
- Industrial processes are a heterogenous group; some allow capture relatively easily, providing low-priced CO2 for EOR or other uses.
- Hydrogen is increasingly attracting interest as a low-carbon energy carrier for industry, heating and long-distance transport (aeroplanes and ships). Hydrogen made from steam reforming of natural gas with CCS is likely to be significantly cheaper than that made from electrolysis of water with low-carbon electricity.

Costs for CCS can be expressed either as the cost of the power produced (for coal- or gas-fired plants), or the cost per tonne of CO2 captured (comparing the plant to a reference facility without CCS). Estimates vary widely because of:

- The lack of real-world experience with full-scale and comparable plants.
- Comparison of first-of-a-kind (FOAK) with nth-of-a-kind (NOAK) where costs have been reduced by learning and experience.
- Different underlying assumptions on scale, efficiency, fuel prices, material prices, location, technology choice, cost of capital, etc.
- Inclusion / exclusion of transport and storage costs.

Estimated capture costs for FOAK and NOAK plants in the US are shown in FIGURE 3.

FIGURE 3 CAPTURE COSTS (US) [vii]



CCS IS A MAJOR PART OF EMISSIONS MITIGATION IN MOST SCENARIOS TO LIMIT WARMING TO 1.5-2°C

Costs for capture from coal and gas power, iron and steel, and cement are relatively high but could be reduced to around ~$40-50 per tonne with experience and technology development. That is well within the range of likely carbon taxes or the EU emissions trading system over the next few years. For processes yielding CO2 directly, capture costs are already low, around $20/tonne. On these figures, the cost of generated electricity would rise around 30-60% with CCS (the rise in consumer prices would be less because of transmission and distribution costs. The cost of cement would be most affected, although it forms a relatively small part of the cost of a construction project. Natural gas, fertiliser and ethanol would see only trivial cost increases of 2-4%.

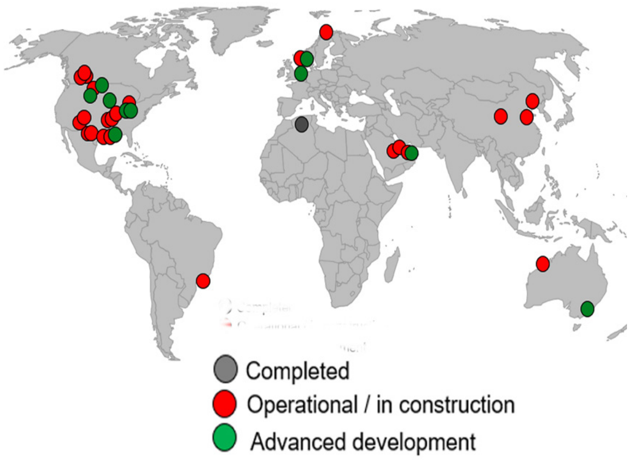
Current CCS methods do not capture all the CO2 emitted, but a typical value of 95-99%. Therefore, there are still some residual emissions, which would have to be accepted (and pay any applicable carbon charge), or offset with, for example, bio-sequestration. In the long term, these residual emissions would limit the overall potential of CCS when very deep reductions are required. However, some new techniques under development have close to 100% capture.

CCS HAS ACCELERATED IN RECENT YEARS BUT STILL REMAINS WELL SHORT OF REQUIRED LEVELS

CCUS did not feature widely in the Nationally Determined Contributions (NDCs) submitted in terms of the Paris Agreement. 13 countries, plus the EU, mentioned it in their submissions, including major oil producers (Iran, Iraq, Saudi Arabia, UAE, Norway, Mexico) and major emitters (China, EU, Japan, South Africa). The US, of course, has announced its withdrawal from the agreement, while several major oil and gas producers did not mention CCUS. Strangely, Canada and Australia who have active projects today, did not include CCUS in their NDCs.

Current large-scale CCS projects with geologic storage / EOR are clustered in North America, the wider North Sea area, the Gulf, Australia and north-east China (FIGURE 3). There is a distinct lack of projects in Latin America, Africa, much of the Middle East, the former Soviet Union, and South and South-east Asia.

FIGURE 4 CURRENT LARGE-SCALE CCS PROJECTS[viii]



The quantity of captured and permanently stored CO_2 has increased only slowly over the past decade, from about 12 Mt/year in 2010 to 25 million tonnes of anthropogenic CO_2 in 2019. By comparison with TABLE 1, this needs to scale up by a factor of 14 over the next decade to meet the median figure, and by 110 times by 2050.

The pipeline of projects also saw severe attrition over this decade, with about 160 Mt/year of potential in 2010 (including operating, under construction, planned and proposed) dropping to about 65 Mt/year in 2017 as many projects were cancelled, before rising to almost 100 Mt/year in 2019. But the quantity of capture in construction fell over this period, meaning that new projects quickly have to move into construction to keep progress going. The 2030 target requires a portfolio of about 350 Mt/year of existing and new projects, and these need to start construction by 2025-6 at the latest, given the lead-time to enter service.

CCS IS TECHNICALLY QUITE MATURE...

CCS, although often still described as an "unproven" technology, is actually quite mature in its typical applications. The separation of CO_2 from other gases, its transport by pipeline, and injection into the subsurface, are standard processes widely used since the 1970s.

Extensive study indicates that carbon dioxide will be trapped safely in well-chosen underground storage sites for geological time (thousands to millions of years) with minimal leakage[ix] . CO_2-saturated water is denser than other subsurface brines and so tends to sink, while CO_2 reacts with various minerals to form solid substances. Experience at the longest-running CCS project, Sleiper in Norway, indicates no leakage after 24 years of operation[x].

Global underground storage capacity is estimated at 8000-50000 Gt[xi], compared to 1200 Gt that would be stored up to 2100 in the IPCC's 'Fossil Fuel' scenario, which has very high use of CCS/BECCS. Underground storage capacity is assessed as more than sufficient in all the regions likely to apply CCS on a large scale.

More innovative methods of capture are under development and could lower costs. For instance, NET Power's gas-fired turbine uses CO_2 as the working fluid and produces high-pressure CO_2 as an output. The company estimates that, because of the turbine's higher efficiency, the NOAK plant could produce electricity for the same cost as conventional gas power plants. Versions that fire coal or produce hydrogen are also under development[xii].

CCS IS TECHNICALLY QUITE MATURE…

Beneficial uses of CO2 for making solid minerals, cement, synthetic fuels and so on are mostly in the research or demonstration stage.

- Carbfix has demonstrated that CO2 can be stored in basalt in Iceland, where it forms stable minerals[xiii].
- Oman has one of the world's largest exposures of olivine-containing minerals, which react readily with CO2 to form magnesite (magnesium carbonate) and quartz[xiv].
- Mine tailings, including from mines for platinum-group metals, chromite, diamonds and nickel, contain minerals that can be carbonated, with potential to offset 22-57% of mine emissions[xv].
- Various CO2-containing cements are being developed, for instance by Solidia and LafargeHolcim[xvi].
- Lanzatech and Cemvita have technologies to produce chemicals and polymers from carbon dioxide.
- Air Co, a New York-based start-up, has turned from making vodka from air-captured CO2 to producing hand sanitiser to tackle the COVID-19 pandemic[xvii].
- Liquid Wind, a Swedish renewable fuel developer, is working with Siemens to develop methanol plants using renewable hydrogen and captured CO2 as feedstock.

…BUT HAS SIGNIFICANT COSTS AND REQUIRES A BUSINESS CASE

Inadequate progress so far has mostly been the result of policy. Carbon prices have been low (see the Al-Attiyah Foundation Issue 14, February 2020 'Carbon Pricing: Lessons for the Middle East') or absent in much of the world, too low to make CCS projects commercially viable. In contrast, renewables have benefited from specific support mechanisms such as feed-in tariffs, auctions for capacity, and portfolio standards, to the point where costs have fallen to make them commercially viable without subsidies (see also the Al-Attiyah Foundation Issue 15, March 2020 'Renewable Energy Policies: Work in Progress').

CCS will always require a carbon price or equivalent regulation to be adopted, except where an economically beneficial use (such as EOR) exists for the captured CO2.

Governments have been willing to pay relatively small amounts for R&D, pilots and early-stage project development. But, in the absence of a mandatory price on carbon, they have generally not been ready to pay the large amounts in direct subsidies required to move projects into full scale construction.

Several CCS projects have suffered from cost overruns. Most notably, the Kemper County Integrated Gasification Combined Cycle (IGCC) in Mississippi, was intended to cost $2.4 billion but eventually cost $7.1 billion, and the coal-burning part of the project has to be abandoned. However, the cost overruns and economic unviability were related to the gasification unit and the sharp drop in natural gas prices relative to coal, not to the carbon capture technology itself.

In contrast, Petra Nova in Texas has the more straightforward post-combustion capture applied to a coal boiler, the CO2 being used for EOR, and started operations in December 2016 according to plan[xviii].

CCS, being associated with the oil, gas and coal industries, has generally not enjoyed the same support from the public and environmental groups as renewables. Norwegian NGO Bellona is a rare example of a pro-CCS environmental organisation[xix]. More recently, controversy has arisen on the question of negative emissions via BECCS or DAC. Some environmental groups strongly oppose its inclusion in models as an "unproven" or "risky" technology that would lock in dependency on fossil fuel[xx].

CCS projects on power or industry are relatively complex – they involve at least two major players, usually a power/industrial company and an oil company. Vertically integrated CCS projects – where an oil company captures CO2 from its own operations – have therefore been more common. Power companies are usually not skilled in geology and reservoir engineering; oil companies are not used to running utilities. But in future, more complex business models will be essential for most projects.

Some early CCS projects, such as the Shell Barendrecht project in the Netherlands, encountered initial public opposition, based on perceived fears of CO2 leakage or other dangers. Since then, projects have tended to prefer storage in offshore locations, remote areas, or depleted oilfields where community issues are less serious.

IMPACT OF NEW POLICY APPROACHES

CCUS is now widely supported by a few major international organisations. The International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC) have addressed CCUS extensively. The Oil and Gas Climate Initiative (OGCI), a coalition of leading oil companies, has identified it as a key technology. The Global Carbon Capture and Storage Institute, established by the Australian government, is probably the leading international advocacy body.

It is necessary to note three recent developments that are important for the progress of CCS.

Carbon taxes and caps have risen in price and become more widely adopted. Permits under the EU Emissions Trading System (ETS) have increased to €25 ($27) per tonne, towards the range needed for the lower-cost CCS options (FIGURE 5).

FIGURE 5 EU ETS PRICE[xxi]

The US's new 45Q tax credit offers $50 per tonne for CO2 captured and stored permanently, or $35 per tonne for CO2 used in EOR. Again, this is enough to incentivise lower-cost capture options, although the implementation of the credit by the tax authorities has been slow. Meanwhile, California's low-carbon fuel standard credit was trading at around $210 per tonne in early 2020[xxii], before the impact of COVID-19. These incentives have spurred coal plants, such as Milton R. Young in North Dakota[xxiiii], and oil companies, to consider CCS and CO2-EOR. At least 23 projects have been identified by the Clean Air Taskforce as planning to make use of the 45Q incentives[xxiv].

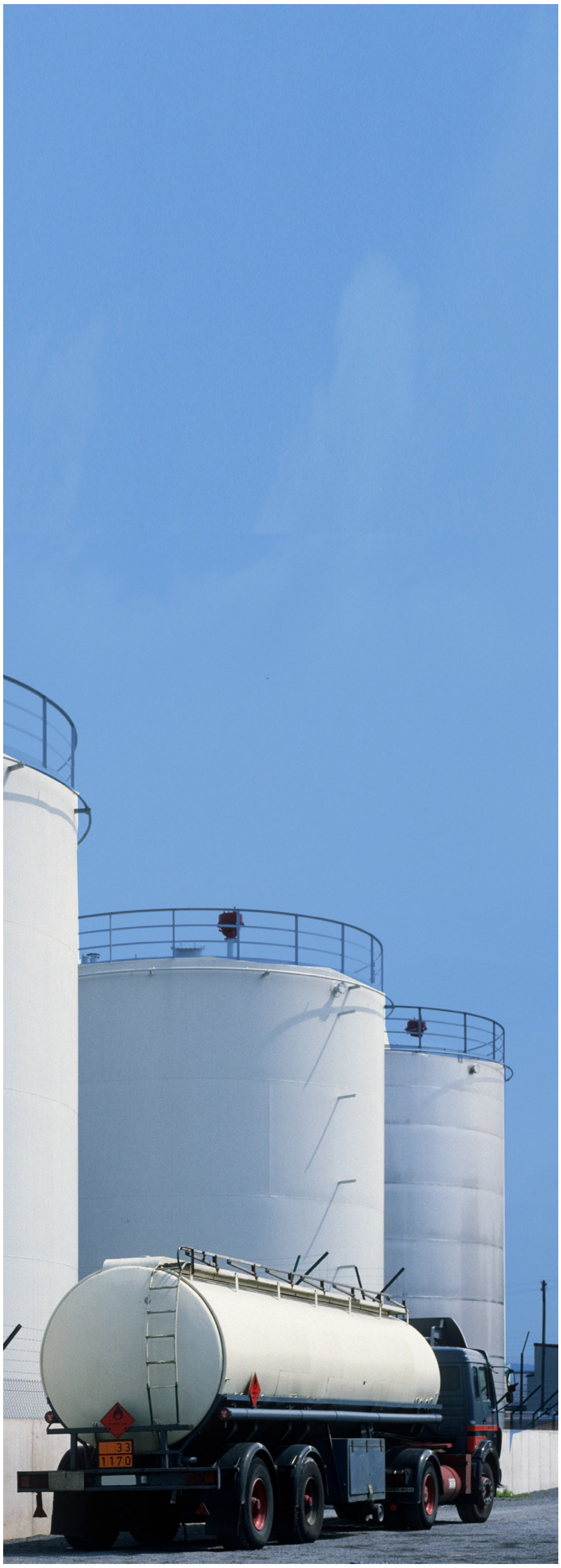
Carbon footprint and disclosure has become increasingly important to the EU, which is considering setting standards for the production or imports of carbon-intensive materials, such as fuels, in the bloc. This would encourage exporters of products such as LNG to reduce their carbon footprint, or risk exclusion from the EU market. Producers of gas with a high natural CO2 content, such as Gorgon in Australia, would therefore need CCS to reduce their carbon footprint in a competitive way. Alternatively, imported goods might face tariffs based on their carbon footprint[xxv].

Several major oil companies, including Shell[xxvi] and BP, have pledged to be carbon-neutral by 2050. Therefore, in order for oil and gas to remain an integral part of the global energy mix by 2050, these oil majors and/or their

customers would have to rely on carbon offsets from DAC, BECCS or bio-sequestration projects.

CCS hubs have gained traction. These group several emitters with a pipeline or tanker route to gather and transport CO2, to a storage location. This can reduce costs and complexity for individual emitters who may not be capable individually to implement the whole CCS chain. Examples include:

- CarbonSAFE in Illinois, USA, with sources including coal and ethanol plants;
- Alberta Carbon Trunk Line, transporting CO2 from a refinery, a fertiliser plant and other emitters for EOR;
- Santos Basin in Brazil, which gathers CO2 from ten offshore oil facilities and reinjects it for EOR;
- Northern Lights in Norway, which will take carbon dioxide from cement and waste plants for storage in the North Sea, forming an open-access infrastructure for any emitter to use;
- CarbonNet in Victoria, Australia, gathering CO2 from proposed coal-to-hydrogen plants;
- Qatar, which plans to capture 5 Mt/year from its LNG plants by 2025;
- Other CCS hubs, could be found in Rotterdam, Amsterdam; Teesside (UK); Xinjiang (China); Humber (UK); and North Dakota (US).



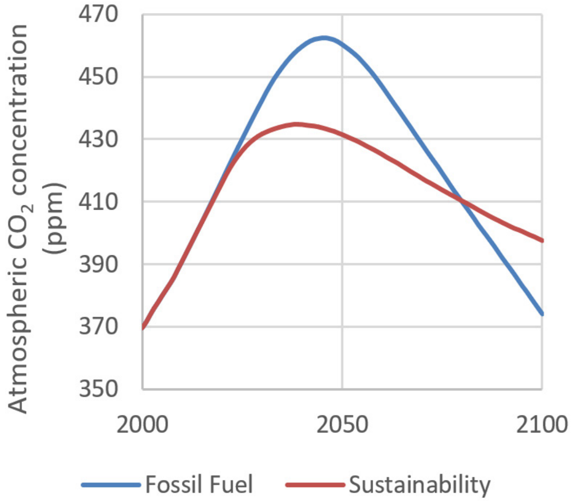
THE USE OF DIRECT AIR CAPTURE (DAC) TECHNOLOGY IS BECOMING WIDESPREAD

DAC technologies are being pioneered by several start-up companies, for instance Climate Engineering, Climeworks[xxvii] and Global Thermostat[xxviii]. Occidental Petroleum is working with Carbon Engineering to use DAC to deliver 0.5 Mt per year of CO2 for EOR in Texas. At the moment, Climeworks estimates its cost at $500-700 per tonne, too high for widespread deployment. However, Climeworks is hoping to reduce this to $100 per tonne through technology improvements and economy of scale of large-scale deployment, as has happened for other modular energy technologies such as wind, solar and batteries.

DAC is currently more expensive and more energy and water-intensive, than CO2 drawdown by reforestation / afforestation or soil carbon enhancement; but requires much less land. The two approaches should not be seen as competing alternatives but rather complementary to one another.

DAC / BECCS can be seen as essential part of "overshooting" scenarios, where atmospheric CO2 concentrations temporarily exceed the limit required for climate stabilisation at 1.5°C or 2°C of warming, before they are drawn down to the desired levels (FIGURE 6). While such scenarios are risky, they may be essential or unavoidable given the slow pace of emissions reductions to date.

FIGURE 6 'OVERSHOOTING' CO2 CONCENTRATION SCENARIO[xxx]

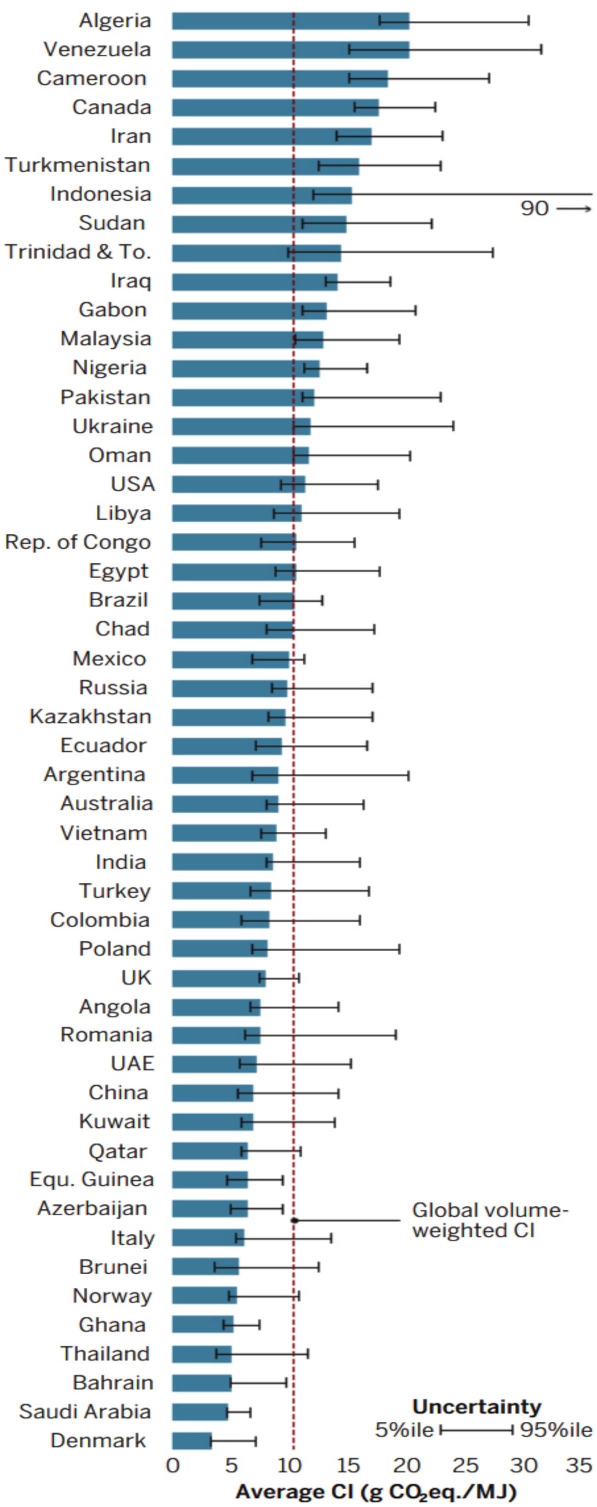


IMPLICATIONS FOR MAJOR OIL AND GAS PRODUCERS

CCS has been recognised for at least 20 years as an essential part of the oil and gas industry's long-term future. Non-combustion uses of hydrocarbons (to make long-lived petrochemicals) are only a small part of demand. To have a future that does not involve either drastic hydrocarbon demand decline or dangerous climate change (or both), large-scale CCS is essential. For dispersed emissions, particularly from transport, DAC/BECCS will be needed for carbon-neutrality.

CO2-EOR is a commercial technology today, capable of using large quantities of carbon dioxide. Global oil production has an average greenhouse gas footprint of 10.3 g CO2e per MJ but varies widely between countries (FIGURE 7). Along with energy efficiency, flaring and methane leakage reduction, CCS is a crucial technology to reduce this GHG footprint. It may be required to preserve market access to the EU and other areas.

FIGURE 7 GHG FOOTPRINT OF UPSTREAM OIL PRODUCTION[xxxi]



Several oil- and gas-producing regions have uniquely good conditions for CCS, with emitters and sinks (mature fields and saline aquifers) in close proximity, technical expertise and a reasonable level of public acceptance. These include the Gulf Cooperation Council (GCC) states, the US, western Canada, north-eastern China and Australia. The North Sea has growing policy support but higher costs.

The widespread use of CCS could lead to long-term continuing use of coal, and so be negative for gas demand. However, new coal power is already widely uncompetitive against gas and renewables, and CCS would increase its costs further. Some low-cost coal resources, as in Australia, might be used to produce hydrogen. But the changing energy landscape of the past decade suggests gas will now probably be the bigger winner of continuing fossil fuel use with CCS.

Recent progress on the technology, policy and cost of CCS is promising, but adoption remains far too limited to reduce the industry's emissions significantly.

Major oil and gas producers should not wait passively for others to develop the required technologies, projects and business models. This would mean that progress would be too slow and might not evolve in a favourable direction.

Hydrocarbon producers who take a lead on CCS could encourage policies to price CO2 emissions and/or limit high carbon footprint imports, in order to benefit as early movers. They could co-invest with international oil companies and climate-friendly governments to develop CCS projects as carbon offsets and commercial-scale demonstrations. Active participation in organisations such as the GCCSI and OGCI is important.

CONCLUSIONS

CCS needs a combination of three factors to achieve its potential, and at the scale required by many climate scenarios.

The first is an enabling market framework, most likely carbon pricing or tradable emissions caps, though it could also be in the form of a carbon footprint standard. The rulebook for Article 6 of the Paris Agreement (governing international cooperation on cutting emissions, including carbon trading[xxxii]), once agreed, could provide scope for implementation of joint CCS projects, for instance between the EU and some States in the GCC.

The second is a pipeline of large-scale projects, including hubs and transport systems, that will demonstrate and implement CCS on all the key emitters (gas and coal power, BECCS, aluminium, cement, hydrogen production, oil refinery, etc.) and DAC.

The third is focussed investment in technology development and deployment to reduce capture costs and to prove the beneficial uses of CO2. Such investments could be a future profitable investment for hydrocarbon-exporting countries, a hedge against future climate developments, and a way to develop new domestic industries.

APPENDIX

i.Qamar Energy analysis of data in https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces/2
ii.https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf
iii .https://www.globalccsinstitute.com/wp-content/uploads/2020/04/Thought-Leadership-Scaling-up-the-CCS-Market-to-Deliver-Net-Zero-Emissions-Digital-1.pdf , https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces/2, https://www.iea.org/reports/tracking-industry/ccus-in-industry-and-transformation
vi .World Energy Outlook 2019, Sustainable Development scenario
v.https://ieta.org/resources/COP24/Misc%20Media%20Files/Dec5/Dec5SE2_5.pdf
vi.https://energypost.eu/an-independent-global-energy-forecast-to-2050-part-4-of-5-nuclear-biomass-and-ccs/
vii.https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf
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OUR MEMBERS

Currently the Foundation has over fifteen corporate members from Qatar's energy, insurance and banking industries as well as several partnership agreements with business and academia.

Our partners collaborate with us on various projects and research within the themes of energy and sustainable development.

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